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Original Article

ATLAS study: Design, athletic performance, and sex-specific regression models for muscle strength in the Greek population

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ABSTRACT

Purpose: ATLAS is a cross-sectional study aiming to investigate environmental and genetic determinants of athletic performance in healthy Greek competitive athletes (CA). This article presents the study design, investigates the muscle strength performance (MSP) of 289 adult and teenage CA, exercisers, and physically inactive individuals (PI), and proposes predictive models of MSP for adults.
Methods: Muscle maximal, speed, and explosive strength (MMS/MSS/MES) at unilateral maximal concentric flexion and extension contraction (FC/EC) were evaluated using Biodex System 3 PRO™ at 60 °/s, 180 °/s, and 300 °/s, while additional performance markers were assessed through field ergometric testing. Participants were interviewed about their lifestyle, dietary habits, physical activity, injury, and medical history. Body composition was assessed via bioelectrical impedance. gDNA was extracted from biochemical samples and then genotyped. Statistical analysis was conducted using IBM SPSS Statistics v21.0 and R.
Results: Age, fitness, and sex impacted correlations of MSP with body composition and anthropometric measurements ($p < 0.05$). Among CA, females outperformed males in accuracy ($p < 0.001$) while, males outperformed females in anaerobic power, MSP, speed, and endurance ($p < 0.001$). Adult CA outperformed exercisers and PI in MMS, MSS, and MES ($p < 0.05$). Multiple linear regression models, with predictors age, FFM, body extremity, training load explained the majority of variation in MMS (R^2_{adj}:71.4%–88.9%), MSS (R^2_{adj}:64.8%–78.4 %), and MES (R^2_{adj}:52.7%–68.4 %) at EC, FC, and their mean ($p < 0.001$).
Conclusions: Muscle-strengthening strategies should be customized according to individual fitness levels, body composition, and anthropometric measurements. The innovative sex-specific regression models assessing MMS, MSS, and MES at EC and FC provide a framework for personalizing rehabilitation and skill-specific training strategies.

List of abbreviations			
AP	Athletic performance	Mean MMS	Mean of peak torque at flexion and extension contraction for MMS
R^2_{adj}	Adjusted R-squared	Mean MSS	Mean of peak torque at flexion and extension contraction for MSS
abj	Adjusted	Mean of PT at FEC	Mean of peak torque values at flexion and extension contraction
β	Beta-value	*Med*	Median
BF	Body fat	MET	Metabolic equivalent of task
BF%	Percentage of the body mass that is fat	MET-min/week	Total metabolic equivalent of task, calculated as minutes per week

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(*continued*)

List of abbreviations

BIA	Bioelectrical impedance analysis	MES	Muscle explosive strength
BM	Body mass	min/week	Minutes per week
BMI	Body mass index	mmHG	Millimeters of mercury
BMR	Basal metabolic rate	MMS	Muscle maximal strength
BP	Blood pressure	MSP	Muscle strength performance
CA	Competitive athletes	20MSR	20-m shuttle run test
cm	Centimeter	Mod	Model
Con	Concentric	MSS	Muscle speed strength
CPC	Center of perception cognition	MUAC	Mid-upper arm circumference
d	Day	*N*	Total sample size
DBP	Diastolic blood pressure	*n*	Number of participants
DEE	Daily energy expenditure	NCA	Non-competitive athletes
EC	Extension contraction	Ns	Non-significant
EI	Energy intake	N·m	Newton-meters
Eq	Equation	*p*	p-value
IPAQ	International Physical Activity Questionnaire	PA	Physical activity
IPAQ-GR	International Physical Activity Questionnaire for the Greek population	PAL	Physical activity level
FC	Flexion contraction	PI	Physically inactive individuals
FEC	Flexion and extension contraction	PT	Peak torque
FFM	Fat-free mass	RMR	Resting metabolic rate
FFM%	Percentage of body mass that is fat-free	*SE*	Standard error
FFMI	Fat-free mass index	s	Second
FFQ	Food frequency questionnaire	*SD*	Standard deviations
gDNA	Genomic DNA	SBP	Systolic blood pressure
HC	Hip circumference	TBW	Total body water
IOC	International Olympic Committee	VAT	Visceral adipose tissue
IOTF	International Obesity Task Force	WC	Waist circumference
IQR	Interquartile range	WHR	Waist-to-hip ration
kcal	Kilocalories	WHO	World Health Organization
kg	Kilogram	y	Year
m	Meter	*zBMI*	z-score body mass index
Mean MES	Mean of peak torque at flexion and extension contraction for MES		

1. Introduction

Optimizing human performance involves a holistic approach that considers both extrinsic factors, such as training load, nutrition, and lifestyle, as well as intrinsic factors, such as individual characteristics.[1,2] Specifically, physiological attributes like body composition, muscle fiber composition, neurophysiology, and biochemistry—shaped by age, sex, and genetic predisposition—can explain variations in aerobic and anaerobic capacity, injury tendency, trainability, and natural talent.[2–4] Prioritizing muscle mass is crucial for physical function and overall health, and its preservation and growth are positively related to greater muscle strength performance (MSP).[5] Muscle strength can be categorized into different types: muscle maximal strength (MMS), muscle speed strength (MSS), and muscle explosive strength (MES). Each type, generated during flexion contraction (FC) and extension contractions (EC), is essential for sport-specific skills, such as jumping, sprinting, and rapid direction changes.[4,6] Resistance training enhances muscle strength, which in turn reduces injury risk and improves force generation, force-time characteristics, and strength-power potentiation.[4,7] An imbalance in muscle mass can signal reduced athletic capabilities, increased injury risk, and health conditions like sarcopenia and malnutrition.[8–10] Therefore, assessing muscle strength is crucial in both athletic and clinical settings, contributing to the individualization of rehabilitation and muscle-strengthening strategies.[7,9–11]

Over time, various regression models have been proposed for muscle strength assessment due to their practicality.[5,10,12–14] However, several areas remain underexplored. For instance, many studies concentrate on specific age groups (e.g., elderly[10] or young adults[14]) and characteristics (e.g., low physical activity [PA][5,10,12,13]), often neglecting other demographics such as middle-aged adults, mostly due to difficulties in their requirements. Additionally, existing regression models for muscle strength assessment have predominantly been developed and validated within specific ethnic groups.[5,10,12,14] Ethnicity can influence anatomical characteristics and muscle strength performance due to genetic, cultural, and lifestyle differences, potentially limiting the applicability of muscle strength models across diverse populations.[15] Moreover, while studies often include sex as a variable in their models, developing sex-specific models could further minimize sex-related bias in statistical analysis.[13,16] Further, most models rely on static measurements of muscle strength.[5,14,17] Instead, incorporating dynamic assessments that measure muscle function during movement could provide more relevant data.[12,13] Additionally, some proposed models have prioritized anthropometric variables, such as circumferences and height,[5,13,18] with fewer attempts incorporating potentially more influential factors like fat-free mass (FFM) and physical activity levels (PAL).[10,12] Integrating these factors could improve the accuracy and explanatory power of the models, as they have a greater impact on muscle strength.[1,4,6,19,20]

In this context, the overall aim of the ATLAS study is to examine the interaction of genetic and lifestyle factors with athletic performance (AP) in competitive athletes (CA) and non-competitive athletes (NCA) of Greek origin. The present paper focuses on 1) presenting the ATLAS study in terms of design and descriptives, such as anthropometric measurements, body composition, injury history, PA and AP markers, 2) examining the relationship between body composition, anthropometric measurements, and injury history with MSP, by sex, developmental stage, and fitness status and 3) developing sex-specific predictive models for MMS, MSS, and MES assessment during EC and FC.

2. Materials and methods

2.1. Experimental design

The ATLAS cross-sectional study aims to investigate the environmental and genetic determinants of AP in Greek adults and adolescent CA and NCA. Volunteer characteristics, recruitment selection, and assessments are presented in Fig. 1. To facilitate robust analytical outcomes, participants were stratified by sex, age, injury incident, and fitness status. The present paper doesn't focus on the relationship between AP and genetics, or dietary habits.

2.2. Ethical approval

The study was conducted following the guidelines of the Declaration of Helsinki and received approval from the Research Ethics Committee of Harokopio University of Athens (Protocol numbers: 42/28-05-2014, Γ-3347/20-07-2021, Γ-1173/15-03-2022). All participants were thoroughly informed about the study procedures orally and provided their informed consent by signing the consent form before participating.

2.3. Criteria for classification in fitness groups

To understand and analyze PA habits and distinguish professionals from recreational athletes and exercisers, as well as exercisers from those with low PAL, participants were categorized into three fitness status groups—CA, exercisers, and physically inactive individuals (PI)—based on the classification algorithm proposed by McKinney et al. The CA group was composed of individuals exercising at moderate (3.1–6 total metabolic equivalent of task, calculated as minutes per week [MET-min/

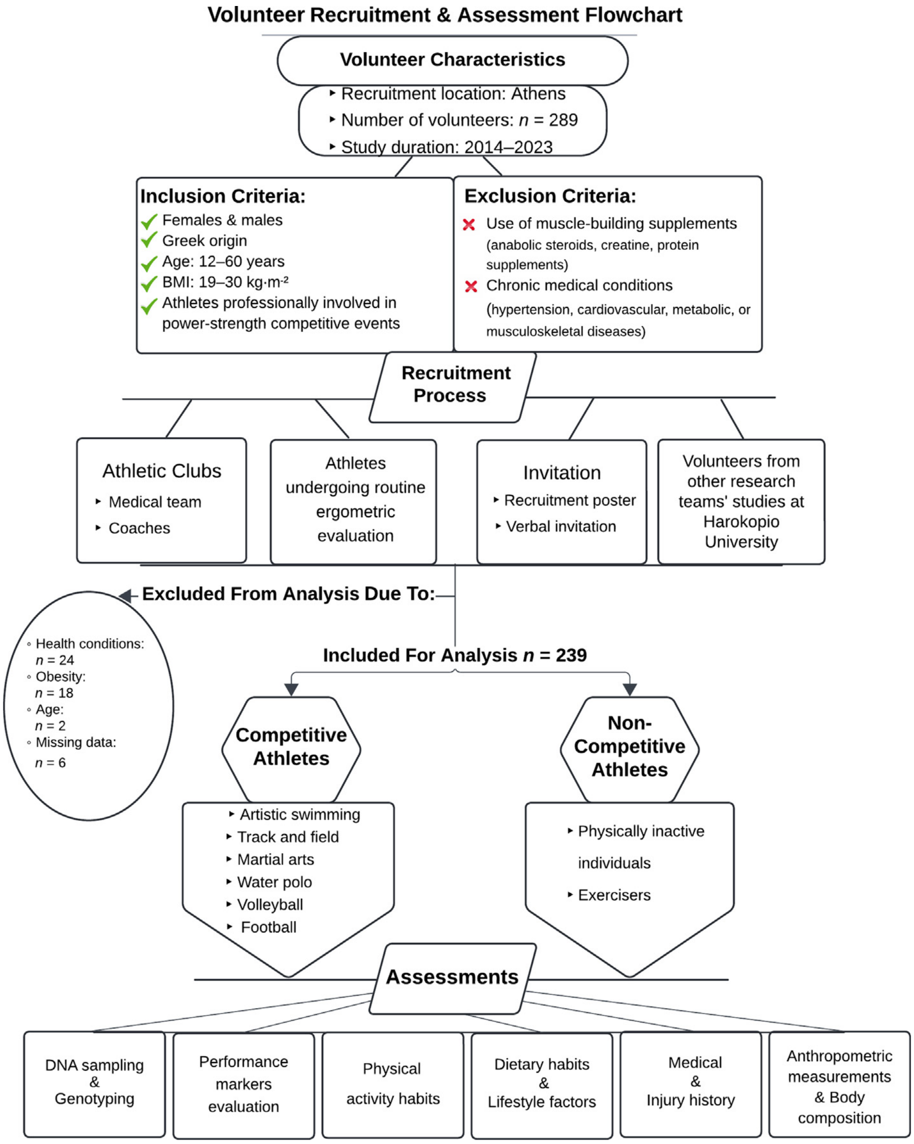

Fig. 1. Flowchart illustrating the volunteer recruitment process, inclusion and exclusion criteria, and the final categorization of participants into groups, along with the comprehensive assessments performed on the final sample. Abbreviations: BMI: body mass index; m: meter: kg: kilogram; *n*: number of participants.

week]) to vigorous ($>$ 6 MET-min/week) intensity for 6 h or more per week, aiming to improve their AP and engage in official competitions. The exercisers group consisted of individuals exercising at moderate to vigorous intensity for less than 6 h per week, aiming to maintain health and fitness or for pleasure, occasionally participating in recreational tournaments. The PI group included individuals engaging in any PA for less than 2 h per week, not meeting the minimum recommended levels of low-intensity exercise ($<$ 3 MET-min/week).[21]

2.4. *Physical activity assessment*

Daily PAL was assessed using the short form of the International Physical Activity Questionnaire for the Greek population (IPAQ-GR) and data were analyzed according to International Physical Activity Questionnaire (IPAQ) guidelines. The training load of the participants was calculated based on the volume, intensity, frequency, and type of physical exercise as outlined in their weekly training and/or competition plan. Exercise intensity was quantified as MET-min/week, according to MET values from the compendium of PA. The work metabolic rate was estimated based on individuals' 24-h energy expenditure. The 24-h PAL was calculated by dividing daily energy expenditure (DEE) by resting metabolic rate (RMR),[22] using the equation (Eq. (1)):

$$PAL = DEE \div RMR$$

RMR was determined using the Schofield equations for men and women, and DEE[23] was calculated using Eq. (2):

$$DEE = \frac{\sum(MET \times Activity\ duration) \times Weight}{60}$$

MET: represents the energy cost of activities, from sleep/rest with MET = 0.9 to running at 12 mph with MET = 19.0.

Activity duration: represents the time spent on each activity, in minutes.

Weight: represents the individual's weight in kilograms.

2.5. *Anthropometry*

For anthropometric measurement, height was measured to the nearest 0.5 cm using a portable stadiometer (Seca 700). Waist, hip, and mid-upper arm circumferences (WC, HC, MUAC, respectively) were measured with non-extensible soft tape. Body composition, including total body mass (BM), body fat (BF), percentage of the body mass that is fat (BF%), FFM, percentage of body mass that is fat-free (FFM%), visceral adipose tissue (VAT), basal metabolic rate (BMR), and total body water (TBW), was assessed using bioelectrical impedance analysis (BIA) via a Tanita appliance (BC-418MA), accurate to the nearest 0.1 kg. During measurements, subjects were barefoot, had removed metal objects, and wore light clothing (0.3 kg deducted).

2.6. Dietary habit assessment

Dietary habits were assessed by a semi-quantitative food frequency questionnaire (FFQ), three 24-h dietary recalls, and an eating behavior questionnaire. Portion sizes were evaluated with the help of images and standardized measurements.

2.6.1. Food frequency questionnaire

The food frequency questionnair (FFQ) reporting 172 items consumed over the last year was used to evaluate dietary habits.[24] Participants reported the frequency of food and beverage consumption using images and servings to describe portion sizes. The standardized serving size per food item was multiplied by the reported frequency (never, 1–3 times/month, 1–2 times/week, 3–4 times/week, 5–6 times/week, and 1 time/d) to calculate the daily consumption.[25] Regularly consumed meals not mentioned in the FFQ were also recorded. The FFQ was completed either through an interview conducted by the dietitian or by self-reporting under the dietitian's supervision.

2.6.2. 24-h dietary recall and eating behavior questionnaire

Dietary intake was assessed with three representative 24-h dietary recalls—one for a weekday involving training sessions, one without, and one for a weekend day.[26] Participants were asked to describe their consumption of food, beverages, water, alcohol, and any supplementation or drug intake during the previous 24 h, using standardized measurements for accuracy. The first recall was obtained on the examination day, and the second and third through telephone contact within 3–10 days via interview with a trained dietitian. Eating behavior was assessed using a self-reported questionnaire administered under the supervision of a trained dietitian.[26]

2.7. Clinical evaluation

Overall health profile was assessed through medical and family health history and blood pressure (BP) measurements. Family and medical history were obtained through self-reported interviews, including current or past family disease status and medication intake information. Hypertension was assessed via BP measurements using a digital automatic blood pressure monitor (Omron M6 [HEM-7001E]), and the measurements were evaluated according to the 2020 International Society of Hypertension Global Hypertension Practice Guidelines.

2.8. Injury history assessment

An ad hoc questionnaire was used to assess self-reported injury history, administered during an interview with a trained professional. A small proportion of participants was interviewed through telephone contact. The classification of injuries by type and severity was conducted according to the system outlined in the consensus statement of the International Olympic Committee (IOC). Injury incidents, caused during athletic or non-athletic events by contact or non-contact with another object or person, were recorded. Injuries were categorized as overall injuries, and those affecting body extremities assessed using isokinetic dynamometry. For each injury, the nature, year of onset, body location, method, and duration of recovery were documented. Injuries were categorized as minor if recovery lasted 1–7 days, moderate if it lasted 8–28 days, and serious if it lasted more than 28 days and up to 6 months. Recovery duration was counted in days starting from the day of the injury incident up to individuals returning to their usual daily or training activities. Recovery time was calculated as weighted recovery time, considering the total number of injuries, their severity, and the duration of each recovery.

2.9. Athletic performance markers evaluation

During the ergometric evaluation, volunteers had no prior training in isokinetic dynamometry and were free from injuries or health conditions that could affect their performance. To ensure optimal results, participants abstained from ergogenic aids, alcoholic beverages, and intense PA for 24 h before the test. Additionally, participants fasted for 4 h and wore appropriate sports attire during the assessments. To evaluate AP markers, CA completed both field and laboratory ergometric testing, while NCA underwent only laboratory testing to ensure standardized conditions and minimize variability in the testing environment.

2.9.1. Field ergometric testing

AP markers—endurance, anaerobic power, speed, and accuracy—were evaluated using field ergometric tests tailored to each sport, as detailed in Table 1. Field sports athletes performed their tests on a 400 m track and field stadium with six lanes, while water sports athletes used a 50 m swimming pool maintained at a stable temperature of 26 °C. All athletes completed a 30-min sport-specific warm-up: jogging and dynamic stretches for field sports, and freestyle swimming along with pool exercises for water sports. The tests included adequate rest periods to allow for heart rate normalization. Verbal instructions were provided to ensure consistent testing conditions.

2.9.2. Laboratory ergometric testing

2.9.2.1. a isokinetic dynamometer - measurement protocols.

To assess different types of muscular strength, participants were subjected to laboratory ergometric testing with an isokinetic dynamometer, Biodex System 3 PRO ™ (Biodex Medical Systems, Inc, Shirley, NY),[27] systematically calibrated throughout the study according to manufacturer instructions.

The protocol for each sport was selected by our research team based on the specific nature of the sport (see Table 1). The dominant limb was tested, as it contributes to a greater generation of MSP.[28] To determine limb dominance, CA were asked to indicate the extremity used to perform their primary significant sport-specific task[28] (e.g., kicking a ball, executing a serve, performing a kick, ball throwing, sculling upside down), while NCA were asked to indicate the extremity used to write or kick a ball.[29] Following maximal concentric unilateral isokinetic protocols, MMS was assessed at 60 °/s (first set, 5 repetitions), MSS was assessed at 180 °/s (second set, 5 repetitions), and MES was assessed at 300 °/s (third set, 5 repetitions). For the interpretation of maximal effort, for MMS, MSS, and MES at FC and EC, peak torque (PT) in Newton-meters (N·m) was used, representing joint axis motion at the greatest force point.[30] The mean of peak torque at flexion and extension contractions (mean of PT at FEC) was calculated for each velocity to represent MMS, MSS, and MES, respectively.

2.9.2.2. b isokinetic dynamometer measurement.

To maintain consistency, measurements were conducted by the same examiner following a standardized protocol described in the manufacturer's manual and suggested by other studies.[31] Before the ergometric test, participants performed dynamic stretching for 3 min to warm up and prepare muscles. Subjects were either in an upright position or seated with specific body parts strapped (chest, quadriceps) depending on the ergometric protocol performed. To ensure correct body positioning on the isokinetic dynamometer, the instructions specified in the manual regarding the specific symmetric location of anatomical parts (joints; shoulder, lateral epicondyle, knee) with the axis of rotation and the lever of the instrument, were strictly followed. As a familiarization process with the isokinetic

Table 1

Field and laboratory ergometric tests for athletic performance markers evaluation.

Sport/Ergometric test Performance characteristics	Water polo	Artistic swimming	Volleyball	Football	Martial art	Track and field	NCA (exerciser/ physically inactive)
Endurance	Swimming 200 m freestyle	Swimming 200 m freestyle	20MSR	20MSR	20MSR	20MSR	–
Anaerobic power	5 kg medicine ball above head	5 kg medicine ball above head	400 m run	400 m run	400 m run	400 m run	–
Speed	Swimming 25 m freestyle	Swimming 25 m freestyle	Running 100 m sprint	Running 100 m sprint	Running 100 m sprint	Running 100 m sprint	–
Accuracy	Scoring goal[a,b]	“Thrust” test[a,b]	Targeted serving over the net[a,b]	Scoring goal[a,b]	Kicking dummy at key locations[b]	Overhead medicine ball throw test[a,b]	–
MMS[c]	[d]Isokinetic shoulder evaluation 60 °/s	[e]Isokinetic shoulder evaluation 60 °/s	[f]Isokinetic shoulder evaluation 60 °/s	[g] Isokinetic knee evaluation 60 °/s			Isokinetic [g]knee and [d]shoulder evaluation 60 °/s
MSS[c]	[d]Isokinetic shoulder evaluation 180 °/s	[e]Isokinetic shoulder evaluation 180 °/s	[f]Isokinetic shoulder evaluation 180°/s	[g] Isokinetic knee evaluation 180 °/s			Isokinetic [g]knee and [d]shoulder evaluation 180 °/s
MES[c]	[d]Isokinetic shoulder evaluation 300 °/s	[e]Isokinetic shoulder evaluation 300 °/s	[f]Isokinetic shoulder evaluation 300 °/s	[g]Isokinetic knee evaluation 300 °/s			Isokinetic [g]knee and [d]shoulder evaluation 300 °/s

Note.

protocols· †

Abbreviations: NCA: non-competitive athletes; 20MSR: 20-m shuttle run test; MMS: muscle maximal strength; MSS: muscle speed strength; MES: muscle explosive strength; Con: concentric; kg: kilogram; m: meter.

[a] From a distance of 6m.

[b] completed 6 attempts.

[c] Evaluated with isokinetic dynamometer Biodex system 3 pro.

[d] Shoulder external/internal rotation/(90 degrees of abduction) (40°–45° away, 55° toward) (protocol: isokinetic unilateral Con/Con: test 60/60,180/180,300/300).

[e] Shoulder pattern: external/internal rotation/(modified neutral) (50° away, 90° toward) (protocol: isokinetic bilateral 180/180,300/300 contraction: Con/Con).

[f] Shoulder diagonal standing isokinetic unilateral external/internal rotation 90° abduction Con/Con: test 60/60,180/180,300/300.

[g] Knee extension/ flexion (away 0°, toward 135°), protocol: isokinetic unilateral extension/flexion Con/Con: test 60/60,180/180,300/300.

dynamometer and as a special warm-up, participants performed 3 sub-maximal EC and FC before each set, under the examiner's guidance. Throughout the ergometric test, participants were verbally encouraged to perform with maximal effort. A 90-s resting time between the three sets was implemented to avoid fatigue, allowing for greater force generation and sufficient preparation for the next set.

2.10. *Genotyping analysis*

For DNA analysis, buccal swabs were initially collected during recruitment at the athletic facilities, and genomic DNA (gDNA) was extracted using the Buccal-Prep Plus DNA isolation kit.[32] Additionally, blood samples were collected from a subset of individuals during their lab visits, with gDNA extracted from these samples using the iPrep™ PureLink™ gDNA isolation kit (Invitrogen Ltd, Invitrogen Corp, USA).[33] DNA samples were genotyped using the following arrays: 1) Illumina GSA BeadChip MD v3,[34] 2) Illumina HumanOmniExpress BeadChips (Illumina, San Diego, USA),[34] 3) the Affymetrix Axiom PMDA chip,[35] and 4) Infinium CoreExome-24 BeadChip, Illumina genome-wide SNP array.[36]

2.11. *Statistical analysis*

The statistical processing of data was performed using IBM SPSS Statistics v21.0, as well as the R statistical package.[32–34] Variables distribution was evaluated using the Kolmogorov-Smirnov test and the Chi-Square Goodness-of-Fit Test. Differences in variables among the groups were assessed using the independent samples *t*-test and ANOVA for the normally distributed variables and the Mann–Whitney *U* test and Kruskal–Wallis test for the non-normally distributed variables. Normally distributed data are presented as means ± standard deviation (*SD*) and non-normally distributed data as median (*Med*) and interquartile ranges (*IQR*). For qualitative variables, relative frequencies are shown. Pearson correlations analysis was used to examine the correlation of MSP with body composition and anthropometric measurements by sex, age, and fitness status. The level of statistical significance was set at $\alpha = 0.05$. To develop the optimal regression models for MSP, predictive variables identified in the literature—such as age, BM, height, FFM, BF, body mass index (BMI), body extremity evaluated (knee/shoulder), training load, PAL, injury history, recovery time from injury, and number of injuries—were examined for their relationship with the dependent variables MMS, MSS, and MES using simple linear regression with the entry method. Identified significant explanatory variables (*p*-value [*p*] < 0.05) after testing for correlations among them, were further included in multiple regression analysis. The final predictive models were created using the enter method, eliminating variables that didn't contribute to optimal outcomes. For non-normally distributed independent variables, a decimal logarithm transformation was implemented to meet the assumption of constant, and the values of coefficients were exponentiated to facilitate interpretation. Bonferroni correction was applied to the final models p by dividing them by four.

3. Results

BMI for adults was calculated according to International Obesity Task Force (IOTF) recommendations and classified into the following categories: underweight (< 18.49 kg/m^2), normal weight (18.5–24.99 kg/m^2), overweight (25–29.99 kg/m^2), and with obesity (≥ 30 kg/m^2). For teenagers, the *z*-score body mass index (*zBMI*) was calculated based on World Health Organization (WHO) growth standards and classified as follows: underweight (< -2), healthy weight (−2 to 1), overweight (> 1), obesity (> 2), and severe obesity (> 3). To examine the effect of developmental stage (puberty and adulthood) on MSP, participants were categorized into two age groups: teenagers (< 18 years) and adults (≥ 18 years).

3.1. Participants descriptives

As shown in Table 2, teenage female CA compared to their male counterparts presented lower values of *zBMI* (0.62 vs 0.99, $p = 0.006$), FFM (40.87 vs 54.59, $p < 0.001$), MUAC (25.53 vs 29.52, $p < 0.001$), WC (68.18 vs 77.90, $p < 0.001$), HC (92.20 vs 96.80, $p = 0.003$), and WHR (waist-to-hip ratio) (0.74 vs 0.81, $p < 0.001$). Detailed subsample descriptives are provided in Appendix Table A1.

Moreover, adult females, had lower values for BMI (22.55 vs 24.60, $p = 0.002$), FFM% (72.71 vs 85.02, $p < 0.001$), TBW (33.30 vs 47.75), WC (74.40 vs 83.70, $p < 0.001$), WHR (0.74 vs 0.83, $p < 0.001$), MUAC (29.00 vs 32.73, $p < 0.001$), but higher BF% (27.26 vs 15.03, $p < 0.001$), compared to adult males (Table 3).

Comparing participants by fitness status, CA exhibited lower BMI (23.10 vs 25.42, $p < 0.001$), BF (15.70 vs 25.80, $p < 0.001$), and VAT (2.28 vs 6.00, $p < 0.001$) compared to PI. CA also had higher FFM and training load than both exercisers (82.78 vs 80.06, $p < 0.001$; 4 430.00 vs 1 255.00, $p < 0.001$) and PI (82.78 vs 73.78, $p < 0.001$; 4 430.00 vs 225.50, $p < 0.001$). Additionally, exercisers had higher FFM (80.06 vs 73.78, $p < 0.05$) and training load (1 255.00 vs 225.50, $p < 0.05$) compared to PI. Detailed subsample descriptives for adult participants are provided in Appendix Table A2.

Table 2
Anthropometric measurements, body composition, and training load of teenage competitive athletes, by sex.

Variables	Total		Female		Male		
	N	Mean ± *SD*	*n*	Mean ± *SD*	*n*	Mean ± *SD*	p[a]
Sex	97	100%	30	30.9%	67	69.1%	
Age (y)	97	14.90 ± 1.43	30	14.47 ± 1.55	67	15.11 ± 1.34	NS
Height (m)	97	1.70 ± 0.09	30	1.62 ± 0.06	67	1.73 ± 0.07	< 0.001
BM (kg)	97	64.52 ± 11.61	30	54.25 ± 8.40	67	69.12 ± 9.78	< 0.001
zBMI (kg/m^2)	97	0.87 ± 0.62	30	0.62 ± 0.69	67	0.99 ± 0.56	0.006
MUAC (cm)	96	28.28 ± 3.14	30	25.53 ± 2.41	66	29.52 ± 2.60	< 0.001
WC (cm)	96	74.86 ± 6.94	30	68.18 ± 5.31	66	77.90 ± 5.28	< 0.001
HC (cm)	96	95.36 ± 7.21	30	92.20 ± 7.81	66	96.80 ± 6.49	0.003
WHR	96	0.79 ± 0.05	30	0.74 ± 0.06	66	0.81 ± 0.03	< 0.001
BF (kg)	95	12.70 ± 5.00	29	13.37 ± 3.71	66	12.36 ± 5.53	NS
FFM (kg)	87	50.02 ± 9.62	29	40.87 ± 5.47	58	54.59 ± 7.80	< 0.001
TBW (kg)	31	30.7 (6.1)[b]	28	29.95 ± 4.07	3	47.93 ± 7.40	< 0.001
Training load (MET-min/week) [a]	97	10 800.00 (3 750)[b]	30	4 860.00 (2 948)[b]	67	10 800.00 (0.01)[b]	< 0.001

Note.
Total volume, intensity and type of physical activity during training and/or competition spent per week. WHR were calculated as follows: WHR = WC (cm)/HC (cm).
Abbreviations: *p*: *p*-value; *N*: Total sample size; *n*: number of participants; Ns: non-significant ($p > 0.05$); *IQR*: Interquartile Range; *SD*: Standard Deviation; BM: body mass; *zBMI*: z-score body mass index; FFM: fat-free mass; BF: body fat; TBW: total body water; WC: waist circumference; HC: hip circumference; WHR: waist-to-hip ratio; MUAC: mid-upper arm circumference; cm: centimeter; y: year; m: meter: kg: kilogram; MET-min/week: total metabolic equivalent of task, calculated as minutes per week.
[a] *p* of Mann-Whitney *U* test or independent samples *t*-test.
[b] Variables not following a normal distribution are presented as median (*IQR*); The significance level is set at $p < 0.05$.

3.2. Body composition, anthropometric measurements, and muscle strength performance

The correlation of MSP with body composition and anthropometric measurements was tested for adults (Fig. 2A), adult females Fig. A1a, adult males Fig. A1b, adult female CA (Fig. 2B), adult male CA (Fig. 2C), teenagers (Fig. 2D), teenage female CA (Fig. 2E), and teenage male CA (Fig. 2F). The correlation map figures (Fig. 2A–F, 2Aa, b) visually depict the relationships between MUAC, WC, HC, WHR, height, age, BMI, TBW, FFM, BF, and VAT with MMS, MSS, MES at EC, FC, and mean PT at FEC across these groups.

3.3. Sex and athletic performance

Examining athletes' AP capability, by sex (Table 4), female CA outperformed males in accuracy (3.00 vs 0.33, $p < 0.001$). Male CA outperformed females in MMS (71.25 vs 64.89, $p = 0.009$), MSS (63.65 vs 34.30, $p < 0.001$), MES (51.35 vs 34.25, $p < 0.001$), anaerobic power (35.01 vs 23.16, $p < 0.001$), speed (14.14 vs 16.24, $p < 0.001$), and endurance performance (14.85 vs 17.00, $p < 0.001$).

3.4. Age, sex, and muscle strength performance

As presented in Table 5, teenage females outperform teenage males in MMS (all $p < 0.001$), contrarily among adults, males outperformed females in MMS (all $p < 0.001$). Teenage and adult males outperformed their female counterparts at MSS and MES (all $p < 0.001$).

3.5. Fitness status and muscle strength performance

As depicted in Fig. 3A–C, female CA, and male CA outperformed their counterpart exercisers and PI in MMS, MSS, and MES (all $p < 0.05$). Male exercisers outperformed male PI in MMS at FC and the mean of PT at FEC, in MSS at FC, and in MES at the mean of PT at FEC (all $p < 0.05$) (see also Table S1).

3.6. Injury history and muscle strength performance

The effect of injury history on MSP was examined by age and fitness status. Statistically significant differences between groups were found only for adult CA (see Table S2). As depicted in Fig. 4, CA with injury history compared to those without, exhibited higher MMS (Fig. 4A and B), MSS (Fig. 4C and D), and MES (Fig. 4E and F) but only at EC and mean of PT at FEC (all $p < 0.05$). Regarding adult CA injuries, Fig. S1A presents the frequency of injury nature, while Fig. S1Aa-c illustrates their severity. Further details on injury history frequency by age, sex, and fitness status are provided in Table S3.

3.7. Gender-specific regression models for muscle maximal, speed, and explosive strength

Sex-specific multiple regression models were developed to assess MMS, MSS, and MES during both EC and FC of major upper and lower body muscle groups. Table 6 shows the proportion of variation explained by the adjusted R-squared (R^2_{adj}) for MMS, MSS, and MES at EC, FC, and the mean PT at FEC for females and males. The following equation (Eq. (3)) can be used to estimate MSP for each muscle type and contraction in both sexes, using the corresponding β-values and intercepts from Table 6, along with individual age (years), FFM (kg), body extremity (evaluated shoulder or knee), and training load (MET-min/week):

(3): Regression equation for MMS, MSS, and MES estimation:

$$\text{Muscle strength} = \text{intercept} + \text{Age} \times \beta_{Age} + \text{FFM} \times \beta_{FFM} + \text{Body extremity} \times \beta_{Body\ extremity} + \text{Training load} \times \beta_{Training\ load}$$

Muscle strength: For different types of muscle strength and

Table 3

Anthropometric measurements, body composition, and training load of adult participants, by sex and fitness status.

Variables	Total		Female		Male			Competitive athlete		Exerciser		Physically inactive		
	N	*Med* (*IQR*)	*n*	*Med* (*IQR*)	*n*	*Med* (*IQR*)	p^a	*n*	*Med* (*IQR*)	*n*	*Med* (*IQR*)	*n*	Med (*IQR*)	p^c
Age (y)	142	27.69 (16.00)	62	28.80 (16.50)	80	27.00 (14.60)	NS	79	21.43 (9.40)$^{¥}$	19	29.15 (6.10)$^{\$¥}$	44	38.10 (19.30)$^{\$}$	< 0.001
Height (m)	142	1.75 (0.14)	62	1.65 (0.12)	80	1.78 (0.07)	< 0.001	79	1.77 (0.13)$^{\$}$	19	1.70 (0.14)	44	1.68 (0.15)$^{\$}$	0.006
BM (kg)	142	71.91 ± 12.08^{b}	62	62.45 (12.20)	80	75.65 (11.30)	< 0.001	79	70.70 (12.40)	19	73.20 (23.70)	44	74.75 (19.30)	NS
BMI (kg/m^2)	142	24.05 ± 3.05^{b}	62	22.55 (5.40)	80	24.60 (3.40)	0.002	79	23.10 ± 2.84$^{b¥}$	19	24.82 ± 2.49^{b}	44	25.42 ± 3.07$^{b¥}$	< 0.001
FFM (%)	141	79.61 ± 9.70^{b}	62	72.71 ± 7.66^{b}	79	85.02 ± 7.44^{b}	< 0.001	78	82.78 ± 9.08$^{b\wedge}$	19	80.06 ± 8.44$^{b\$}$	44	73.78 ± 8.68$^{b\$\wedge}$	< 0.001
BF (%)	141	20.37 ± 9.47^{b}	62	27.26 ± 7.66^{b}	80	15.03 ± 6.97^{b}	< 0.001	79	15.70 (8.96)$^{\wedge}$	19	18.80 (11.70)	44	25.80 (13.30)$^{\wedge}$	< 0.001
MUAC (cm)	135	31.10 ± 3.43^{b}	59	29.00 ± 2.99^{b}	76	32.73 ± 2.82^{b}	< 0.001	77	30.31 (4.90)$^{\$\#}$	19	33.40 (6.00)$^{\#}$	43	32.45 (4.70)$^{\$}$	0.007
WC (cm)	137	80.74 ± 9.08^{b}	60	74.40 (8.10)	77	83.70 (10.10)	< 0.001	78	77.90 (8.10)$^{\$}$	16	84.10 (17.2)	43	86.50 (14.40)$^{\$}$	0.001
HC (cm)	136	100.35 (7.70)	60	100.80 (8.80)	76	100.05 (7.20)	NS	78	99.07 ± 6.36$^{b¥}$	16	102.20 ± 4.22^{b}	43	103.95 ± 7.33$^{b¥}$	< 0.001
WHR	136	0.80 ± 0.07^{b}	60	0.74 (0.06)	76	0.83 (0.06)	< 0.001	78	0.80 (0.08)	16	0.82 (0.14)	43	0.81 (0.13)	NS
TBW (kg)	136	42.60 (14.70)	60	33.30 (4.50)	76	47.75 (4.30)	< 0.001	74	44.45 (12.80)	18	43.95 (16.00)	44	35.55 (16.40)	NS
VAT	135	2.0 (5.00)	59	2.00 (4.00)	76	2.00 (3.95)	NS	72	2.28 ± 2.60$^{b\$}$	19	3.00 (5.00)$^{\$}$	44	6.00 (6.00)$^{\wedge}$	< 0.001
^{d}Training load (MET-min/week)	142	2 220.00 (3 872.00)	62	2 160.00 (2 768.00)	80	3 600.00 (3 834.00)	0.011	79	4 430.00 (1 750.00)$^{¥}$	19	1 255.00 (1 200.00)$^{¥\$}$	44	225.50 (558.00)$^{\wedge\$}$	< 0.001

Note.

Abbreviations: *p*: *p*-value; *N*: total sample size; *n*: number of participants; Ns: non-significant ($p > 0.05$); *Med*: median; *IQR*: Interquartile Range; *SD*: Standard Deviation; BM: body mass; BMI: body mass index; FFM (%): percentage of body mass that is fat-free; BF(%): Percentage of the body mass that is fat; TBW: total body water; VAT: visceral adipose tissue; WC: waist circumference; HC: hip circumference; WHR: waist-to-hip ratio; MUAC: mid-upper arm circumference; MET-min/week: total metabolic equivalent of task, calculated as minutes per week; cm: centimeter; y: year; m: meter: kg: kilogram.

[a] *p* of Mann-Whitney *U* test or independent samples *t*-test.

[b] Variables follow the normal distribution are presented as mean ± *SD*.

[c] *p* of Kruskal–Wallis or ANOVA test; Significant relationships between groups are indicated as: $^{\wedge,¥}$: for $p < 0.001$ and as: $^{\$,\#}$ for $p < 0.05$; The significance level is set at $p < 0.05$.

[d] Total volume, intensity and type of physical activity during training and/or competition spent per week. WHR and BMI were calculated as follows: WHR = WC (cm)/HC (cm); BMI (kg/m^2) = BM (kg)/Height[2] (m^2).

contraction, replace 'Muscle strength' with the appropriate specific term (e.g., MMS, MSS, or MES at FC, EC, or mean of FEC).

Body Extremity: Replace "Body extremity" with 1 when evaluating the shoulder, or 2 when evaluating the knee.

Example Eq. 3.

For MMS at FC for females:

$$\text{MMS at FC} = 0.05 + (\text{Age} \times -1.03) + (\text{FFM} \times 1.02) + (\text{Body extremity} \times 3.72) + (\text{Training load} \times 1.04)$$

4. Discussion

4.1. *Body composition, anthropometric measurements, and muscle strength performance*

Participants categorized as CA exhibited more favorable body composition measurements compared to exercisers and PI, highlighting the benefits of higher PAL and regular exercise on body composition and overall health.[37,38] When examining the correlation of MSP with body composition and anthropometric measurements, various correlation patterns were observed across groups, highlighting the influence of age, sex, and PA on these variables.[39–42] In detail, TBW, which constitutes approximately 75% of muscle mass showed a positive correlation with MSP, with a 3%–4% reduction in TBW potentially leading to a 2% decrease in MSP.[43] FFM, an independent predictor of muscle strength and essential for force generation,[4] demonstrated a positive correlation with MSP, aligning with evidence that higher FFM is associated with increased MSP.[5] MUAC, which is used as a marker of upper body muscle mass, hand grip strength, and nutritional status, was also positively correlated with MSP in both teenage and adult group.[44] Regarding the correlation between body composition and anthropometric measurements, FFM showed a positive association with MUAC in teenagers, likely attributable to their higher fitness levels as CA and their developmental stage (puberty), which promotes increases in both FFM and MUAC.[44,45] Further, the positive correlation between height and MSP in both age groups is likely due to taller individuals having larger extremities and bones, which may offer improved leverage for muscle development, thereby contributing to greater MSP.[4,19,46]

Concerning the relationship between age and MSP across age groups, a positive correlation was observed in teenagers, likely attributed to developmental factors, hormonal surges, and neuromuscular enhancements characteristic of this growth phase.[47] Conversely, the inverse correlation between age and MSP in adults is likely due to age-related declines in muscle mass, neuromuscular function, and hormonal levels.[5,10,48]

Examining adiposity-related metrics, BF consistently showed an inverse correlation with MSP across groups. VAT also exhibited an inverse correlation with MSP in adults. In contrast, BMI, WC, HC, and WHR demonstrated varying correlation patterns depending on participants' demographics and fitness levels. In general, higher adiposity levels are associated with lower MSP and reduced overall performance, likely due to hormonal imbalances and metabolic dysfunction.[39,45–47] Specifically, visceral adipose tissue releases adipocytokines and cytokines, which disrupt hormonal balance and promote inflammation,[49] leading to

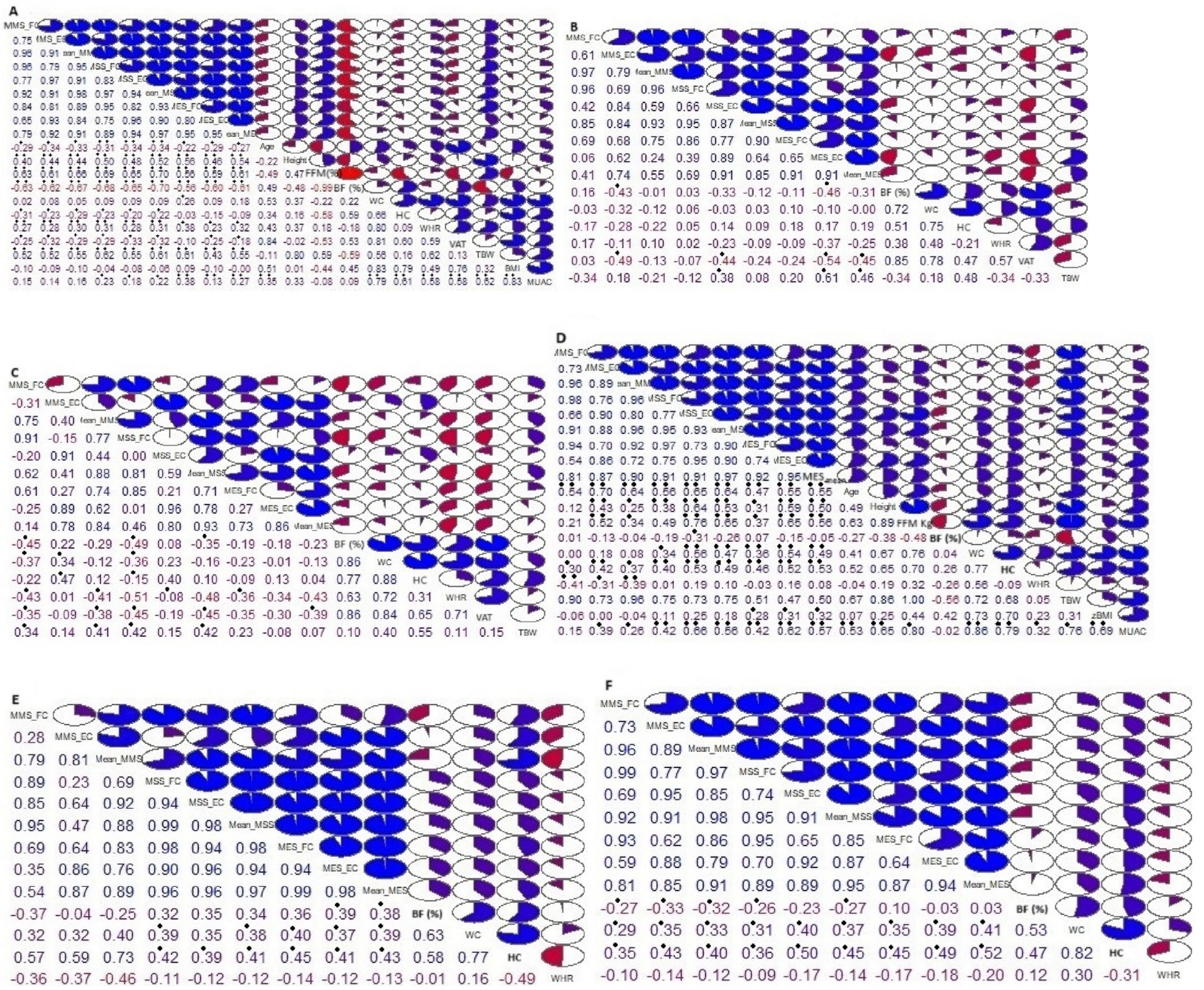

Fig. 2. Visual representation of muscle strength performance correlation coefficients with body composition and anthropometric measurements. Subfigures: Fig. 2A: correlation for total adult sample; Fig. 2B: correlation for adult female CA; Fig. 2C: correlation for adult male CA; Fig. 2D: correlation for teenagers; Fig. 2E: Correlation for teenage female CA; Fig. 2F: Correlation for teenage male CA; Statistical significance: *p* are represented by a dot: ●●: $p < 0.001$; ●: $p < 0.05$; The significance level is set at $p < 0.05$; Blue color: positive correlation; Red color: negative correlation; Purple color: weak or no relationship; The intensity of the color represents the strength of the correlation, with darker shades indicating stronger correlations; The proportion of the disk filled with color indicates the strength of the correlation (1 or −1). The Pearson correlation coefficients (*r*) were classified as minor (0.00–0.09), small (0.10–0.29), moderate (0.30–0.49), large (0.50–0.69), very large (0.70–0.89), almost perfect (0.90–0.99), and perfect (1.0); Abbreviations: *p*: *p*-value; MMS: muscle maximal strength; MSS: muscle speed strength; MES: muscle explosive strength; FC: flexion contraction; EC: extension contraction; FEC: flexion and extension contraction; Mean MMS: mean of PT at FEC for MMS; Mean MSS: mean of PT at FEC for MSS; Mean MES: mean of PT at FEC for MES; PT: Peak Torque; BMI: body mass index; *zBMI*: *z*-score body mass index FFM: fat-free mass; FFM (%): Percentage of body mass that is fat-free; BF (%): Percentage of the body mass that is fat; TBW: total body water; VAT: visceral adipose tissue; WC: waist circumference; HC: hip circumference; WHR: waist-to-hip ratio; MUAC: mid-upper arm circumference.

increased muscle catabolism and reduced levels of anti-inflammatory adiponectin—crucial for muscle glucose metabolism. Chronic low-grade inflammation may further induce insulin resistance, impair protein synthesis, and negatively affect muscle function.[49,50]

Specifically, concerning the relationship of BMI with MSP across two age groups, a positive correlation was found between *zBMI* and MSP in teenage CA. Similarly, Casanova et al. reported a correlation between horizontal and vertical jumps in young male Portuguese futsal players; however, their findings were negative, possibly due to different mechanisms underlying these performance markers.[51] In adults, no correlation between BMI and MSP was found, consistent with the findings of Danneskiold-Samsøe et al.[46] This suggests that BMI may not be a reliable indicator of MSP in non-obese and metabolically healthy adults,[10] as well as for exercisers and CA who typically have higher FFM.[52] BMI primarily reflects weight categories and does not account for body composition, limiting its utility in assessing muscle strength.[53]

Focusing on circumferences, WC was correlated with MSP only in males. Specifically, in adults, WC showed a negative correlation with MSP, consistent with Lockie et al.'s findings of a similar negative correlation between WC and fitness performance in male adults.[18] Conversely, in teenagers, WC and HC were positively correlated with MSP, both when analyzing the combined sample and when examining each sex separately. This positive correlation may be attributed individually or synergistically to training- and growth-related increases in core and hip skeletal muscle,

Table 4
Athletic performance capability of competitive athletes, by sex.

Variables	Total		Female		Male		
	N	*Med* (*IQR*)	*n*	*Med* (*IQR*)	*n*	*Med* (*IQR*)	*p*[g]
MMS (PT, N·m)[d,a]	212	69.83 (97.31)	65	64.89 (54.98)	147	71.25 (119.80)	0.009
MSS (PT, N·m)[e,a]	238	50.40 (60.16)	91	34.30 (38.85)	147	63.65 (74.95)	< 0.001
MES (PT, N·m)[f,a]	214	45.77 (35.94)	91	34.25 (40.10)	123	51.35 (39.35)	< 0.001
Anaerobic power (s)[a]	121	45.14 (36.28)	37	23.16 (37.71)	84	35.01 (32.78)	< 0.001
Speed (s)[b]	122	14.79 ± 1.77[h]	38	16.24 ± 1.71[h]	84	14.14 ± 1.37[h]	< 0.001
Accuracy (scores)[b]	118	0.50 (3)	34	3.00 (2.00)	84	0.33 (1)	< 0.001
Endurance (s)[a]	121	15.34 (3.83)	37	17.00 (7.08)	84	14.85 (7.86)	< 0.001
Training load (MET-min/week)[a,c]	239	4 430.00 (8 979)	92	2 730.00 (4 133)	147	5 280.00 (7 920)	< 0.001
PAL[a]	144	2.08 (0.92)	73	2.30 (0.86)	71	1.93 (0.94)	0.002

Note.
Abbreviations: *p*: *p*-value; *N*: Total sample size; *n*: number of participants; *Med*: median; *IQR*: Interquartile Range; *SD*: Standard Deviation; FEC: flexion and extension contraction; MET: metabolic equivalent; PAL: physical activity levels; MMS: muscle maximal strength; MSS: muscle speed strength; MES: muscle explosive strength; s: second; PT: Peak Torque; N·m: Newton-meter; MET-min/week: total metabolic equivalent of task, calculated as minutes per week.

[a] The highest value shows a greater performance.

[b] The lower value shows a greater performance.

[c] Total volume, intensity, and type of physical activity during training and/or competition spent per week.

[d] MMS is presented as the mean of PT at FEC.

[e] MSS is presented as the mean of PT at FEC.

[f] MES is presented as the mean of PT at FEC.

[g] p of Mann-Whitney U or independent samples *t*-test.

[h] Variables following the normal distribution are presented as mean ± *SD*; The significance level is set at $p < 0.05$.

as well as reduced BF due to their athletic status.[54] Similarly, Liu et al. reported a positive correlation between WC and AP (VO$_2$max) in children and teenagers.[55] Regarding WHR, a correlation with MSP was observed in the combined sample of males and females, but when analyzed by sex, a negative correlation was found only in adult males and adult male CA. Castillo et al. similarly reported sex-specific differences, noting that MSP decreased in males in both high and low WHR categories, while in females, MSP was inversely correlated with WHR across all categories.[56]

The different correlation patterns observed between adiposity-related indices and MSP across sex groups may stem from differences in body fat distribution between males and females.[18,56] Specifically, females typically have higher body fat, which is predominantly distributed in the hips and thighs, while males with the same BMI often accumulate body fat in the trunk, particularly the abdomen.[57] Consequently, these differences in body fat distribution likely explain the correlation patterns observed, as female participants in this study exhibited higher BF and lower WC across all fitness groups than their male counterparts.

Additionally, variations in muscle strength types and contraction forms could influence the correlation between MSP and body circumferences (HC, WC, WHR), as inconsistent patterns have been observed across different age, sex, and fitness groups. Specifically, adult males and teenage male CA exhibited correlations across all muscle strength types, whereas adult male CA showed inconsistent correlations. Conversely, no correlations were found between MSP and HC, WC, or WHR measurements in adult female CA. On the other hand, for teenage female CA, no correlation was observed for MMS, while inconsistent correlations were noted between the measurements and both MSS and MES. These variations in correlation patterns across age, sex, and fitness levels may be attributed to dynamic changes in hormonal levels, muscle mass, and body adiposity during puberty, as well as differences in athletic training, muscle activation, and fiber recruitment strategies.[32,48,58,54,19]

4.2. Sex and athletic performance

Among CA participants in this study, males and females excel in distinct areas, highlighting sex-based differences in AP markers.[59,60] Typically, sex-related characteristics such as hydrodynamics, fatigue resistance, and fat oxidation benefit females in long-duration activities like ultramarathons and ultra-swimming.[60,61] In contrast, males generally exhibit greater aerobic and anaerobic capacities, muscle mass, and cardiovascular efficiency.[59,60,61] Consistent with these trends, male CA participants demonstrate superior performance in anaerobic power, muscle strength, speed, and endurance compared to their female counterparts.

Interestingly, female CA participants outperformed males in accuracy, a crucial skill in precision-based sports assessed through precision shooting or targeting tasks.[62,63] Accuracy, governed by the center of perception cognition (CPC), relies on the perceptual-motor connection[62,63] and can be influenced by factors like motor control, perception-action cycle, kinematics, experience, age, and sex.[60–62] Studies suggest that elite female athletes often use different neuromuscular recruitment strategies than their male counterparts, which provides

Table 5
Muscle strength performance, by age and sex.

Variables	Teenager							Adult				
	Total		Female		Male			Female		Male		
	N	*Med* (*IQR*)	*n*	*Med* (*IQR*)	*n*	*Med* (*IQR*)	*p*[a]	*n*	*Med* (*IQR*)	*n*	*Med* (*IQR*)	*p*[a]
MMS at FC (PT, N·m)	212	69.00 (120.30)	7	137.50 (51.00)	67	39.20 (24.60)	< 0.001	58	63.40 (87.20)	80	170.05 (98.80)	< 0.001
MMS at EC (PT, N·m)	212	66.65 (62.80)	7	87.91 ± 29.04[b]	67	56.23 ± 24.92[b]	0.002	58	54.25 (58.10)	80	123.30 (61.30)	< 0.001
Mean MMS (PT, N·m)	212	69.82 (97.31)	7	113.20 (42.25)	67	43.40 (22.70)	< 0.001	58	58.75 (65.60)	80	150.00 (67.36)	< 0.001
MSS at FC (PT, N·m)	238	52.70 (74.40)	30	16.20 (21.1)	67	33.70 (19.70)	< 0.001	61	53.21 ± 27.38[b]	80	118.73 ± 43.05[b]	< 0.001
MSS at EC (PT, N·m)	238	49.40 (35.13)	30	18.00 (20.00)	67	46.00 (27.70)	< 0.001	61	39.45 ± 22.44[b]	80	84.22 ± 36.80[b]	< 0.001
Mean MSS (PT, N·m)	238	50.40 (60.16)	30	17.17 (18.88)	67	42.15 (22.25)	< 0.001	61	46.33 ± 23.17[b]	80	101.47 ± 37.16[b]	< 0.001
MES at FC (PT, N·m)	214	51.67 (29.18)	30	17.20 (25.0)	65	35.10 (14.10)	< 0.001	61	48.48 ± 18.79[b]	58	84.66 ± 24.53[b]	< 0.001
MES at EC (PT, N·m)	214	43.55 (39.30)	30	19.05 (19.20)	65	44.00 (28.50)	< 0.001	61	39.29 ± 22.33[b]	58	64.68 ± 29.09[b]	< 0.001
Mean MES (PT, N·m)	214	45.77 (35.94)	30	17.33 (20.04)	65	39.80 (19.90)	< 0.001	61	40.05 (32.35)	58	77.30 (25.06)	< 0.001

Note.
Abbreviations: MMS: muscle maximal strength; MSS: muscle speed strength; MES: muscle explosive strength; Mean MMS: mean of PT at FEC for MMS; Mean MSS: mean of PT at FEC for MSS; Mean MES: mean of PT at FEC for MES; *p*: *p*-value; *N*: total sample size; *n*: number of participants; *Med*: median; *IQR*: Interquartile Range; *SD*: Standard Deviation; FC: flexion contraction; EC: extension contraction; FEC: flexion and extension contraction; PT: Peak Torque; N·m: Newton-meter.

[a] *p* of Mann-Whitney *U* test or independent samples *t*-test.

[b] Variables following the normal distribution are presented as mean ± *SD*. The significance level is set at $p < 0.05$.

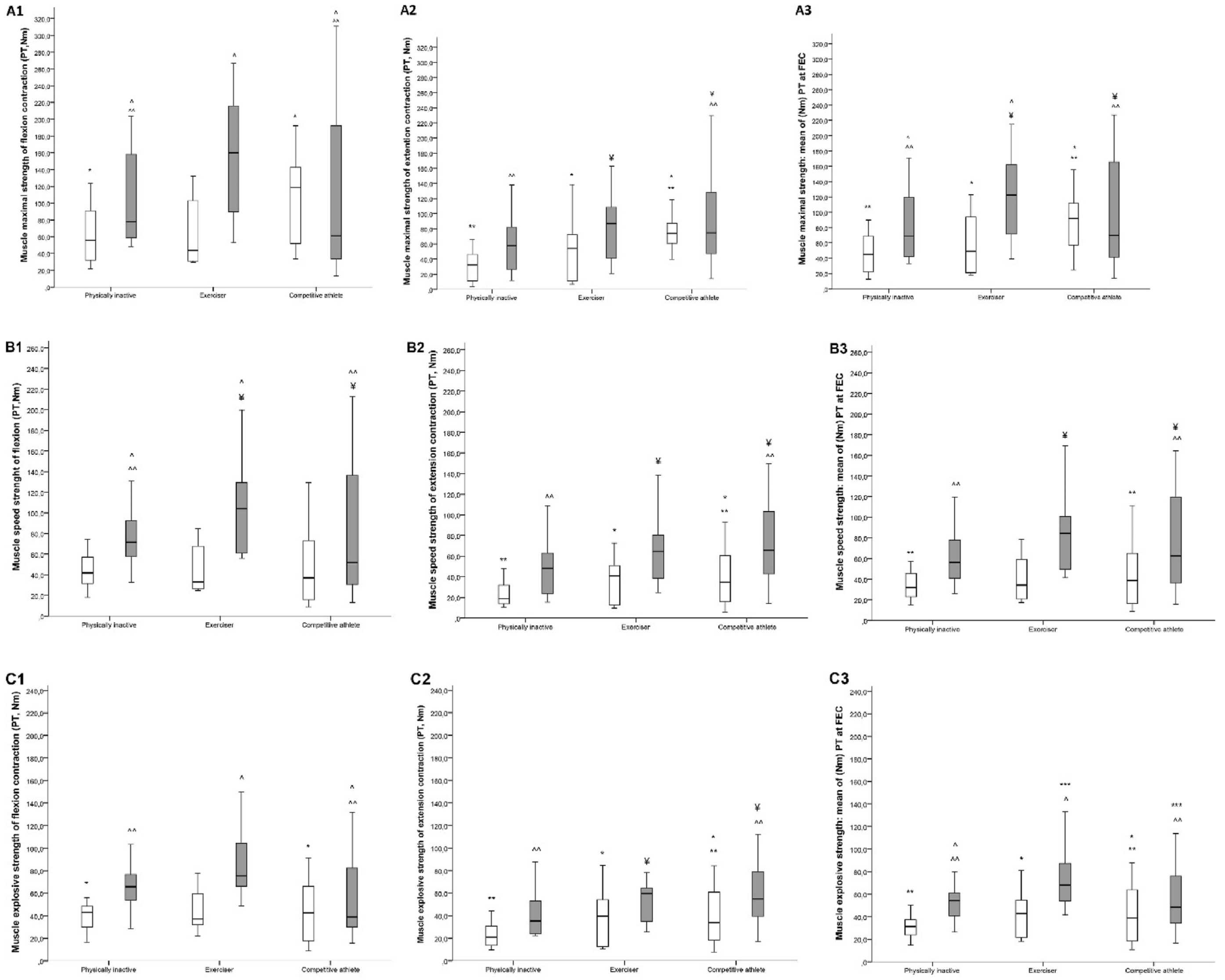

Fig. 3. Box plot depicting muscle strength performance by fitness status in adults. Participants classification: The x-axis represents fitness status, and the y-axis shows different types of muscle strength performance measurements. Females are represented in white, and males in gray. Statistical tests: The statistically significant relationships between groups were assessed using ANOVA and the Kruskal–Wallis test. Statistical significance: The significance level is set at $p < 0.05$. For females, significant relationships between groups are indicated as ** for $p < 0.001$ and as * for $p < 0.05$. For males, significant relationships between groups are indicated as ˆ and ¥ for $p < 0.001$, and as ˆ and *** for $p < 0.05$. Abbreviations: *p*: *p*-value; FEC: flexion and extension contraction; PT: Peak Torque; N·m: Newton-meter.

them with advantages in perceptual speed, accuracy, and fine motor skills, supporting our findings.[20,64]

4.3. Age, sex, fitness level, and muscle strength performance

It is generally expected that males exhibit greater MSP than females due to factors such as enhanced neuromuscular activation, and higher testosterone levels that promote skeletal muscle strength.[6,40,59,55,64–67] Additionally, males typically exhibit a more advantageous distribution of muscle mass, showing 25%–40% more FFM, primarily concentrated in the upper body, compared to females.[59,46,66] Consistent with these factors, both teenage and adult male participants in this study demonstrated higher FFM and MSP compared to their female counterparts. An exception was observed in teenage female CA, who outperformed their male counterparts in MMS. This finding may be attributed to the small sample size of teenage female CA and the relatively minor hormonal impact on muscle mass growth between sexes during puberty, which could contribute to inconsistent results regarding sex-related performance differences.[16,68]

Among fitness groups, both female and male CA outperformed exercisers and PI, as anticipated, given that CA typically engage in higher training load—including resistance training—that leads to muscle hypertrophy and increased muscle fiber recruitment,[1,6] resulting in greater MSP.[4,5] Additionally, the observation that exercisers generally outperform PI in MSP was more pronounced among males. This may be because females often participate in a broader range of less specialized exercises, whereas males typically engage in more intense activities, including resistance training, which results in more favorable MSP outcomes.[4,5,69]

4.4. Injury history and muscle strength performance

Injuries to ligaments, muscles, and tendons typically reduce force production during dynamic movements, with the extent of the reduction depending on the severity of the injury, ultimately leading to decreased MSP.[4,70] Interestingly, in adult CA participants, injury history was inversely associated with MSP. Contributing factors to this outcome might include the injuries affecting non-pivotal joints, resistance training during rehabilitation enhancing connective tissue strength, sufficient

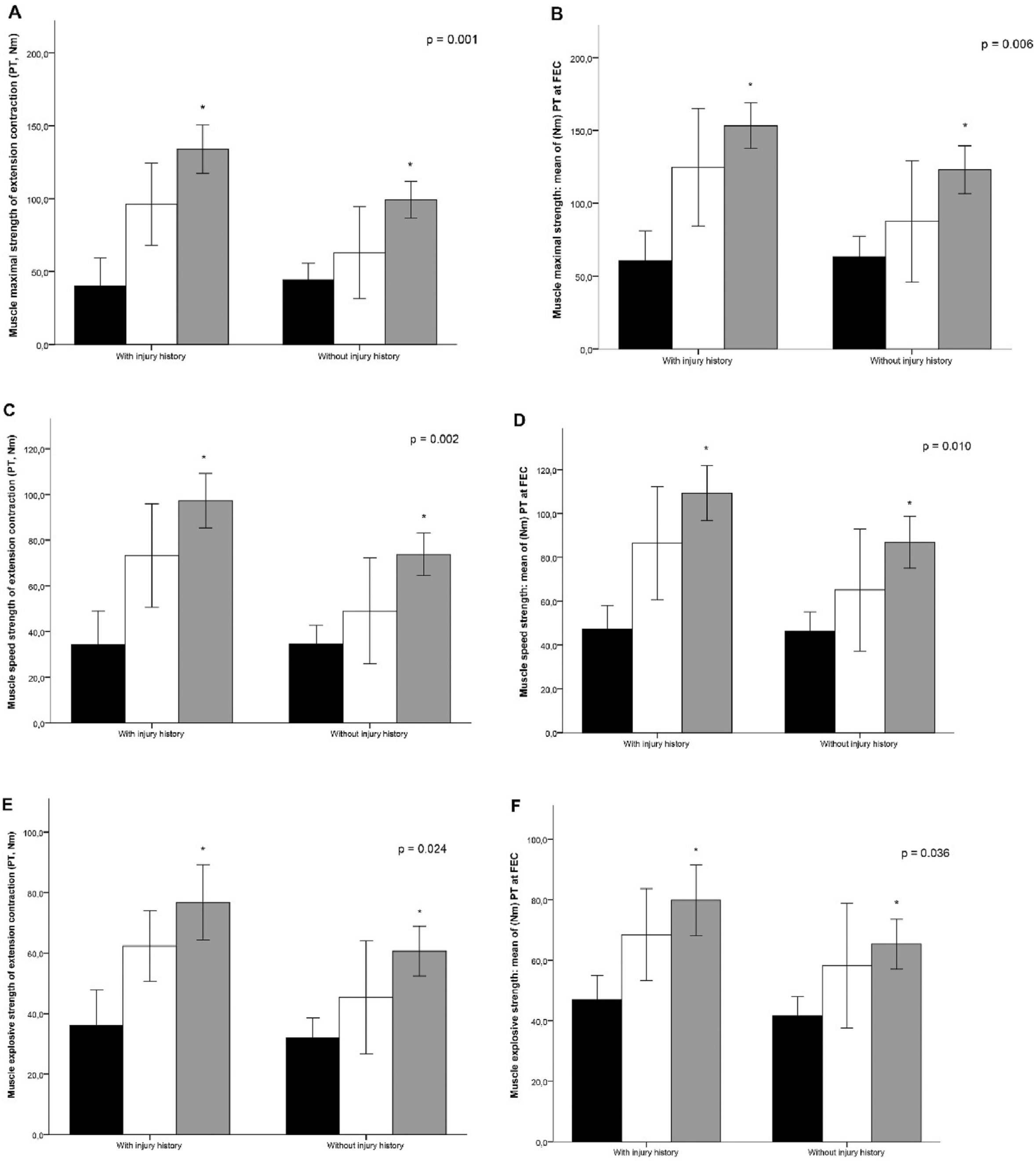

Fig. 4. Graphs depicting the relationship between muscle strength performance and injury history in adults, categorized by fitness status. Participants classification: The x-axis represents injury history incidents, and the y-axis shows different types of muscle strength performance measurements. Competitive athletes are represented in gray, exercisers in white, and physically inactive individuals in black. Statistical tests: independent samples *t*-test and Mann-Whitney *U* test. Injury history follows the expected Poisson distribution based on the Chi-Square Goodness-of-Fit Test. Statistical significance: The level of significance is set at $p < 0.05$. The * denotes statistically significant relationships between groups. Definition: The self-reported variable injury history is defined as an injury sustained during athletic activities by contact or non-contact with an object or person, affecting the dominant body extremity assessed with an isokinetic dynamometer. Abbreviations: FEC: flexion and extension contraction*;* *p*: *p*-value*;* PT: Peak Torque; N·m: Newton-meter.

time elapsed since the incident, and/or compensatory mechanisms leading to full recovery.[4,9,70]

Regarding injury frequency, CA had higher injury rates compared to exercisers (78.5% vs. 42.1%, $\chi^2 = 0.012$; $df = 1$) and PI (78.5% vs. 38.6%, $\chi^2 < 0.001$; $df = 1$), as expected given that CA engaged in more intense PA. Among sex groups, females experienced lower injury incident rates than males (50.0% vs. 70.0%, $\chi^2 < 0.001$; $df = 1$), likely due to sex-related differences in physiology, sport type, and risk-taking behaviors.[70] Across age groups, teenagers reported lower injury rates than adults, which may be attributed to factors such as incomplete anatomical maturation, a higher metabolic rate, and improved rehabilitation capabilities observed during puberty.[9]

4.5. Gender-specific regression models for muscle maximal, speed, and explosive strength

The proposed models for the Greek adult population effectively assess key muscle strength types essential for sport-specific skills. These models explain a substantial proportion of the variation in MMS, with R^2_{adj} values ranging from 71.4% to 88.9%, followed by MSS, with R^2_{adj} values

Table 6

Regression models for assessing MMS, MSS, and MES at EC, FC, and mean PT at FEC in adults, stratified by sex.

Predictors	MMS (PT, N·m) at EC						MSS (PT, N·m) at EC						MES (PT, N·m) at EC					
	Female			Male			Female			Male			Female			Male		
	[a]Mod.1a: $R^2_{adj} = 0.821$			[a]Mod.1b: $R^2_{adj} = 0.806$			[a]Mod.1c: $R^2_{adj} = 0.650$			[a]Mod.1d: $R^2_{adj} = 0.763$			[a]Mod.1e: $R^2_{adj} = 0.611$			[a]Mod.1f: $R^2_{adj} = 0.613$		
	β	SE	[b]p_{adj}	β	SE	[b]p_{adj}	β	SE	[b]p_{adj}	β	SE	[b]p_{adj}	β	SE	[b]p_{adj}	β	SE	[b]p_{adj}
Intercept	−0.46	0.239	0.062	0.18	0.217	0.422	−0.17	0.253	0.504	0.26	0.199	0.193	−0.12	0.180	0.506	0.47	0.263	0.081
Age	−1.02	0.002	0.004	−1.01	0.001	0.040	−1.03	0.002	0.004	1.01	0.001	0.188	−1.03	0.003	0.004	−1.00	0.002	2.140
FFM	1.02	0.004	0.004	1.03	0.002	0.004	1.07	0.005	0.004	1.03	0.002	0.004	1.07	0.005	0.004	1.02	0.003	0.068
Body extremity	2.91	0.049	0.004	4.20	0.050	0.004	2.80	0.051	0.004	3.30	0.046	0.004	2.40	0.054	0.004	2.52	0.060	0.004
Training load[c]	1.02	0.000	0.004	1.00	0.000	0.004	1.06	0.016	0.664	1.00	0.000	0.004	1.00	0.000	0.512	1.00	0.000	0.004

	MMS (PT, N·m) at FC						MSS (PT, N·m) at FC						MES (PT, N·m) at FC					
	Female			Male			Female			Male			Female			Male		
	[a]Mod.2a: $R^2_{adj} = 0.889$			[a]Mod.2b: $R^2_{adj} = 0.818$			[a]Mod.2c: $R^2_{adj} = 0.702$			[a]Mod.2d: $R^2_{adj} = 0.700$			Mod.2e: $R^2_{adj} = 0.535$			[a]Mod.2f: $R^2_{adj} = 0.527$		
	β	SE	[b]p_{adj}	β	SE	[b]p_{adj}	β	SE	[b]p_{adj}	β	SE	[b]p_{adj}	β	SE	[b]p_{adj}	β	SE	[b]p_{adj}
Intercept	0.05	0.208	0.805	0.81	0.186	<0.001	0.46	0.190	0.020	0.97	0.158	<0.001	0.64	0.186	0.001	1.23	0.186	<0.001
Age	−1.03	0.003	0.004	1.02	0.001	0.044	−1.02	0.002	0.004	−1.02	0.001	0.014	−1.01	0.002	0.004	−1.01	0.001	0.112
FFM	1.02	0.003	0.064	1.02	0.002	0.004	1.04	0.003	0.004	1.03	0.002	<0.001	1.05	0.003	0.004	1.02	0.002	0.004
Body extremity	3.72	0.028	0.004	2.74	0.043	0.004	2.70	0.038	0.004	1.95	0.036	<0.001	1.78	0.037	0.004	1.39	0.044	0.028
Training load[c]	1.04	0.009	<0.001	1.00	0.000	0.156	1.00	0.000	<0.001	1.00	0.000	<0.001	0.99	0.002	1.004	1.00	0.002	0.004

	MMS (PT, N·m) mean of PT at FEC						MSS (PT, N·m) mean of PT at FEC						MES (PT, N·m) mean of PT at FEC					
	Female			Male			Female			Male			Female			Male		
	[a]Mod.3a: $R^2_{adj} = 0.831$			[a]Mod.3b: $R^2_{adj} = 0.824$			[a]Mod.3c: $R^2_{adj} = 0.742$			[a]Mod.3d: $R^2_{adj} = 0.784$			[a]Mod.3e: $R^2_{adj} = 0.684$			[a]Mod.3f: $R^2_{adj} = 0.596$		
	β	SE	[b]p_{adj}	β	SE	[b]p_{adj}	β	SE	[b]p_{adj}	β	SE	[b]p_{adj}	β	SE	[b]p_{adj}	β	SE	[b]p_{adj}
Intercept	0.46	0.239	0.062	0.57	0.157	0.001	0.21	0.178	0.024	0.70	0.015	<0.001	0.04	0.144	0.809	0.93	0.194	<0.001
Age	−1.02	0.002	0.004	−1.01	0.002	0.002	−1.02	0.002	0.004	−1.01	0.001	0.004	−1.02	0.002	0.004	−1.00	0.001	0.464
FFM	1.03	0.003	0.004	1.01	0.003	<0.001	1.05	0.003	0.004	1.03	0.002	0.004	1.07	0.003	0.004	1.02	0.002	0.012
Body extremity	3.28	0.036	0.004	3.18	0.050	<0.001	2.64	0.035	0.004	2.35	0.034	0.004	1.93	0.037	0.004	1.75	0.044	0.004
Training load[c]	1.02	0.000	<0.001	1.00	0.000	0.003	1.00	0.000	3.904	1.00	0.000	0.004	1.00	0.000	3.004	1.00	0.001	0.036

Note.

Multiple linear regression models: Dependent variables: MMS, MSS, MES; Predictive variables: age in years; FFM in kg, body extremity (shoulder/knee), training load in MET-min/week.

Abbreviations: MMS: muscle maximal strength; MSS: muscle speed strength; MES: muscle explosive strength; FC: flexion contraction; EC: extension contraction; FEC: flexion and extension contraction; FFM: fat-free mass; MET-min/week: total metabolic equivalent of task, calculated as minutes per week; p: p-value; adj: adjusted; Mod: model; β: β-value; SE: Standard Error; R^2_{adj}: adjusted R-squared; PT: Peak Torque; N·m: Newton-meter.

[a] The p of models is $p < 0.001$.

[b] Adjusted significance level for model variables after Bonferroni corrections set at $p_{adj} < 0.05$.

[c] Training load refers to the total volume, intensity, frequency, and type of physical exercise during training and/or competition spent per week.

between 64.8% and 78.4%, and MES with R^2_{adj} values from 52.7% to 68.4%. A sex-specific approach was employed in these models to account for physiological differences between males and females.[13,30,46] Furthermore, the study's regression models focused solely on adults to avoid potential biases related to anatomical differences arising from the rapid growth experienced by teenagers.[48,66]

The predictive models for MMS exhibited the highest R^2_{adj} values, followed by those for MSS and MES. This suggests that the explanatory variables have a greater contribution to MMS than to MSS and MES. In addition, participants' PT values were also highest during MMS performance, followed by MSS and MES. This pattern may be explained by the fact that MMS is assessed at lower velocities and relies on extensive motor unit recruitment, whereas MES is assessed at higher velocities and depends on the rapid recruitment and synchronization of fast-twitch motor units.[58,71,72] According to Hill's curve, as muscle contraction speed increases, the produced force decreases.[71] Therefore, the differences in motor unit recruitment patterns and muscle fiber utilization likely explain why the explanatory variables have a stronger influence on MMS and a weaker influence on MSS and MES, resulting in the observed decline in R^2_{adj} and PT values.

Furthermore, the models accounted for a higher proportion of the variation in MSP for females, with R^2_{adj} values ranging from 53.5% to 88.9%, compared to males, whose models had R^2_{adj} values between 52.7% and 82.4%. Female models also demonstrated higher R^2_{adj} values for EC, while male models exhibited higher R^2_{adj} values for FC. These dissimilarities can be attributed to sex-related anatomical differences, particularly variations in muscle physiology (e.g., muscle fiber composition), recruitment patterns, and hormonal levels.[4,59] When comparing other proposed models, which focused solely on MMS assessment, Harbo et al.'s sex-specific model for Danes (aged 15–83 years), also explained a higher proportion of variation in MMS for females (9%–63%) compared to males (8%–43%), similar to the findings in our study's models for females.[13] Further, Neder et al.'s gender-combined predictive model developed for Brazilians (aged 20–80 years) explained up to 84% of the variation in MMS.[12] Regarding Stanelle et al.'s models for Americans (aged 18–60 years), it accounts for 68%–83% of the variation in MMS.[5] Notably, both Harbo et al. and Neder et al. used an isokinetic dynamometer for MSP evaluation,[12,13] but Neder et al.'s model included PA as a predictor, likely contributing to its higher predictability compared to Harbo et al.'s model, which did not account for FFM or PA. Conversely, although Stanelle et al. used resistance training equipment to assess MMS, the inclusion of anthropometric measurements such as FFM may have led to similarly high predictability, as in the present study.[12,13] It is also important to consider that the models' predictability could also be influenced by the ethnic diversity of the populations studied.[15]

Among the variables affecting MSP that were tested for inclusion in the regression models, the final models incorporated age, FFM, training load, and body extremity.[1,46,58,73] In detail, FFM, a robust predictor of MSP,[4,5] showed a positive linear relationship with MSP across all models. The variable "body extremity" (shoulder/knee) was a significant contributor, reflecting how differences in joint morphology and axis alignment impact biomechanical dynamics and consequently influence MSP.[58] Specifically, the lower body extremity was associated with greater MSP, possibly due to the involvement of larger muscle groups during motion, compared to the smaller muscle groups of the upper body.[4,13,58]

In terms of the impact of age, it was negatively associated with MSP for both genders, corroborating the age-related reductions in muscle mass.[12,13,44,46] Interestingly, while this relationship was significant across all regression models for females, in males, age was not significantly related to MSS at EC or MES. This lack of significance could be partly explained by the fact that, although aging typically leads to a decline in muscle mass and strength, specific characteristics of fast-twitch fibers in males—crucial for explosive movements—might allow them to maintain functionality better than other muscle fibers as they age.[48] Despite age not reaching statistical significance in males, it was still retained in the model because it is considered a key determinant of isokinetic and isometric muscle strength throughout life stages among both females and males.[12,13,44,46] Specifically, muscle strength is reported to peak in early adulthood and decline afterward,[13] a trend also observed in this study, where being a teenager was positively correlated with MSP, whereas being an adult showed an inverse correlation. Furthermore, aging significantly impacts muscle strength across different muscle groups, with noticeable differences between sexes.[46] For example, in males, muscle health declines linearly but at a slower rate than in females.[46] Additionally, regression models that include age have been shown to explain greater variation in muscle strength for women than for men, as also observed in the study.[13] Including age in the models also maintains consistency with prior research,[5,10,12–14] and helps avoid potential omitted variable bias. Moreover, retaining age allows for the exploration of potential interaction effects with other predictors, thereby enhancing the robustness of the analysis.

Training load, which reflects the volume, intensity, and duration of exercise, is a key factor closely related to muscle mass outcomes and has a well-established dose-response relationship with MSP.[6,19,59,46,66,74,75] The variable's inclusion as a predictor significantly improved explanatory power, as evidenced by an increase in the R^2_{adj} values. Moreover, the training load consistently demonstrated a positive linear relationship across all models, validating its relevance. Despite the unusual standard error (*SE*) of zero, the variable maintained consistently significant p, and the overall improvement in model fit highlighted its influential role in predicting MSP. Thus, the training load was retained in the model, emphasizing its importance in the assessment of MSP.

5. Practical application of regression models

Assessing MMS, MSS, and MES at EC and FC in sports could contribute to more customized, skill-specific training programs and help track MSP variations during the competitive season. Additionally, in rehabilitation, these assessments could aid in monitoring and optimizing patient recovery by planning tailored strength-building exercises.

6. Strengths

To our knowledge, the ATLAS study is the first to aim for a comprehensive investigation of the interactions between AP markers, genetics, and lifestyle factors in the Greek population. Regarding the present findings, the proposed models are unique in their ability to assess three types of muscle strength—MMS, MSS, and MES—at both EC and FC, specifically developed for the Greek population. Furthermore, the use of the gold standard method for assessing muscle strength, the isokinetic dynamometer, along with the models' ability to account for physiological differences between sexes, enhances measurement accuracy and gender-specific precision.

7. Limitations

One of the study's limitations is the reliance on self-reported data, which can be affected by participants' recall ability, social desirability, and interpretation of their history, potentially leading to inaccuracies. To address these concerns and mitigate potential biases, participants were interviewed by trained professionals who provided the necessary guidance and context during the process. In addition, the questionnaires were cross-checked, and sensitivity analyses were conducted during the statistical analysis to ensure the robustness of the data.

Furthermore, BIA was used to assess FFM instead of the gold standard DEXA method, due to the former's increased practicality. Indeed, BIA has also been validated in numerous studies and is known to provide reliable estimates of FFM. Moreover, to further minimize any potential discrepancies, rigorous calibration, and consistency checks were conducted during the measurements, ensuring that the findings remain robust and accurate.

Regarding the proposed models' applicability, their use is currently limited to assessing MSP in healthy adults' knee and shoulder joints. Before these models can be finalized for practical use, their accuracy should be validated in a larger, more diverse cohort. Additionally, it is crucial to investigate their replicability across independent populations, varying life stages, health statuses, and ethnicities to ensure their generalizability and robustness.

8. Future aspirations

A future goal of the ATLAS study is to enhance the understanding of how various factors, such as genetic traits, nutritional status, and other lifestyle factors, interact to influence AP. Furthermore, the study aims to develop a polygenic risk score for AP markers assessment, such as MSP, and evaluate its impact on the predictability of the proposed regression model.

9. Conclusion

Current findings indicate that demographic factors (age, sex), fitness levels, body composition, and anthropometric measurements significantly impact MSP, highlighting the critical need for personalized training and rehabilitation programs. The proposed sex-specific regression models uniquely assess three types of muscle strength—MMS, MSS, and MES—under both EC and FC. To our knowledge, these models are the first of their kind developed for the Greek population. By integrating these MSP assessment models with an individual's body composition and anthropometric data, rehabilitation, and skill-specific training strategies can be further personalized and optimized.

CRediT authorship contribution statement

Natia A. Pogosova: Writing – review & editing, Writing – original draft, Visualization, Supervision, Methodology, Investigation, Formal analysis, Data curation. **Despoina Brekou:** Writing – review & editing, Investigation, Data curation. **Ioanna E. Gavra:** Investigation. **Efthymia A. Katsareli:** Investigation. **Eleni More:** Investigation. **Panagiotis G. Symianakis:** Visualization. **Maria Kafyra:** Writing – review & editing. **Ioanna Panagiota Kalafati:** Writing – review & editing. **Giannis Arnaoutis:** Methodology. **George V. Dedoussis:** Supervision, Resources, Project administration, Methodology, Funding acquisition, Conceptualization.

Ethical approval statement

The study was conducted following the guidelines of the Declaration of Helsinki and received approval from the Research Ethics Committee of Harokopio University of Athens (Protocol numbers: 42/28-05-2014, Γ-3347/20-07-2021, Γ-1173/15-03-2022). All participants were thoroughly informed about the study procedures orally and provided their informed consent by signing the consent form before participating.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix

Table A1

Body composition, blood pressure, physical activity, and dietary characteristics of teenage competitive athletes, by sex.

Variables	Total		Female		Male		
	N	Mean ± *SD*	*n*	Mean ± *SD*	*n*	Mean ± *SD*	*p*[*]
B F (%)	95	19.37 ± 6.77	29	24.10 (6.00)[**]	66	15.90 (10.00)[**]	< 0.001
FFM (%)	87	77.28 ± 6.27	29	75.57 ± 3.77	58	78.13 ± 7.09	NS
FFMI	87	17.15 ± 1.95	29	15.55 ± 1.56	58	17.94 ± 1.60	< 0.001
BMR (kcal)	31	1 434 (206.00)[**]	28	1 424.43 ± 134.32	3	2 049.00 ± 243.62	< 0.001
EI (kcal/d)	16	2 470.78 ± 854.45	12	2 246.07 ± 678.58	4	3 819.05 ± 429.32	0.009
DBP (mmHG)	31	70.29 ± 14.10	7	88.14 ± 11.83	24	65.08 ± 9.88	0.001
SBP (mmHG)	31	114.55 ± 13.66	7	102.33 ± 6.93	24	118.11 ± 13.12	< 0.001
PAL	14	2.33 ± 0.91	12	2.45 ± 0.93	2	1.67 ± 0.26	NS

Note.

FFMI is calculated as follows: FFMI = FFM (kg)/Height^2 (m^2). Abbreviations: *p*: *p*-value; *N*: total sample size; *n*: number of participants; Ns: non-significant ($p > 0.05$); Med: median; *SD*: Standard Deviation; *IQR*: Interquartile Range; FFM (%): percentage of the body mass that is fat-free; BF (%) percentage of the body mass that is fat; BMR: basal metabolic rate; EI: energy intake; DBP: diastolic blood pressure; SBP: systolic blood pressure; PAL: physical activity level; mmHG: millimeter of mercury; kcal: kilocalories; d: day; kg: kilogram; m:meter; FFMI: fat-free mass index.

[*] p of Mann-Whitney *U* test or independent samples *t*-test.

[**] Variables not following a normal distribution are presented as medians (IQR); The level of significance is set at $p < 0.05$.

Table A2
Body composition, blood pressure, physical activity, and dietary characteristics of adult participants, by sex and fitness status.

Variables	Total		Female		Male			Competitive athlete		Exerciser		Physically inactive		
	N	Med (*IQR*)	*n*	Med (*IQR*)	*n*	Med (*IQR*)	*p**	*n*	Med (*IQR*)	n	Med (IQR)	n	Med (IQR)	p***
FFM (kg)	141	58.60 (20.7)	62	45.98 (6.1)	79	65.60 (6.20)	< 0.001	78	60.75 (17.80)	19	59.70 (21.80)	44	48.60 (22.5)	<0.001
FFMI	141	19.07 (4.17)	62	16.67± 1.16**	79	20.88 ± 1.54**	< 0.001	78	19.21 (4.03)	19	20.60 (3.90)	44	17.90 (4.65)	NS
BF (kg)	141	14.67 ± 7.56**	62	17.30 (8.3)	80	10.35 (10.1)	< 0.001	79	10.00 (10.7)$^{\wedge}$	19	14.60 (6.6)	44	18.80 (9.9)$^{\wedge}$	<0.001
DBP (mmHG)	136	88.13 ± 11.93**	56	87.50 (12)	80	87.50 (12.00)	NS	76	88.74 ± 11.21**	18	85.59 ± 17.02**	42	88.13 ± 10.75**	NS
SBP (mmHG)	136	115.50 (14.0)	56	107.17 (12.00)	80	118.50 (10.00)	< 0.001	76	116.79 ± 13.64**	18	116.17 (12.00)	42	112.83 (15.00)	NS
BMR (kcal)	138	1 731.50 (549.0)	60	1 384.50 (176)	78	1 927.50 (218)	< 0.001	75	1 807.00 (485)$^{\$}$	19	1766.00 (596.00)	44	1498.50 (608)$^{\$}$	0.048
EI (kcal/d)	94	2 578.95 ± 889.62**	43	2 261.46 ± 729.16	51	2 846.64 ± 930.41	0.001	43	2 236.74± 668.26**	16	2548.05 ± 649.03**	35	2868.99 ± 1027.81**	0.006
PAL	130	2.08 (0.93)	61	2.29 (0.88)	69	1.94 (0.96)	0.004	68	2.32 (0.95)$^{¥}$	18	2.24 (2.14)$^{\#}$	44	1.78 (0.41)$^{¥\#}$	<0.001

Note.

FFMI is calculated as follows: FFMI = FFM (kg)/Height^2 (m^2).

Abbreviations: *p*: *p*-value; *N*: total sample size; *n*: number of participants; Ns: non-significant ($p > 0.05$); Med: median; IQR: Interquartile Range; SD: Standard Deviation; BF: body fat; FFM: fat-free mass; DBP: diastolic blood pressure; SBP: systolic blood pressure; BMR: basal metabolic rate; EI: energy intake; PAL: physical activity level; mmHG: millimeter of mercury; kcal: kilocalories; d: day; kg: kilogram; m: meter; FFMI: fat-free mass index.

* p of Mann-Whitney *U* test or independent samples *t*-test.

** Variables following the normal distribution are presented as mean ± SD.

*** p of Kruskal–Wallis or ANOVA test; Significant relationships between groups are indicated as $^{\wedge,¥}$ for $p < 0.001$ and as $^{\$,\#}$ for $p < 0.05$; The significance level is set at $p < 0.05$.

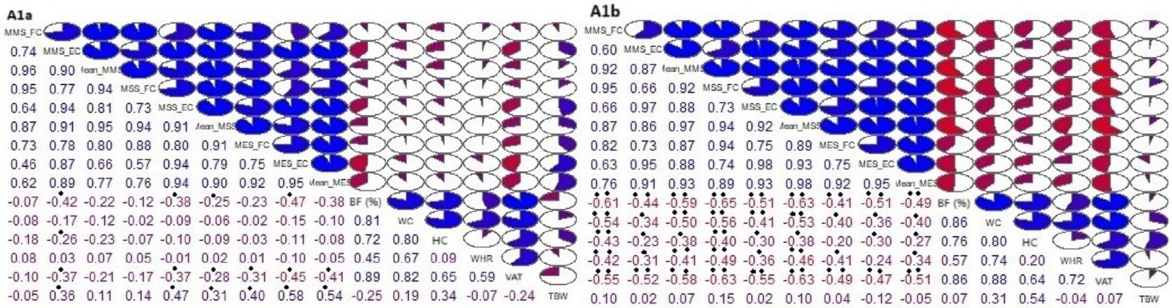

Figure A1. Visual representation of correlation coefficients of muscle strength performance with body composition and anthropometric measurements. Subfigures: Fig. A1a: correlation for adult females; Fig. A1b: correlation for adult males; Statistical significance: p are represented by a dot: ●●: $p < 0.001$; ●: $p < 0.05$; The significance level is set at $p < 0.05$; Blue color: positive correlation; Red color: negative correlation; Purple color: weak or no relationship; The intensity of the color represents the strength of the correlation, with darker shades indicating stronger correlations; The proportion of the disk filled with color indicates the strength of the correlation (1 or −1). The Pearson correlation coefficients (*r*) were classified as minor (0.00–0.09), small (0.10–0.29), moderate (0.30–0.49), large (0.50–0.69), very large (0.70–0.89), almost perfect (0.90–0.99), and perfect (1.0); For interpretation of muscle strength, PT in N·m is used. Abbreviations: p: p-value; MMS: muscle maximal strength; MSS: muscle speed strength; MES: muscle explosive strength; FC: flexion contraction; EC: extension contraction; FEC: flexion and extension contraction; Mean MMS: mean of PT at FEC for MMS; Mean MSS: mean of PT at FEC for MSS; Mean MES: mean of PT at FEC for MES; PT: Peak Torque; N·m: Newton-meter; BF (%): percentage of the body mass that is fat; TBW: total body water; VAT: visceral adipose tissue; WC: waist circumference; HC: hip circumference; WHR: waist-to-hip ratio.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.smhs.2024.11.002.

References

1. Clemente FM, Clark C, Castillo D, et al. Variations of training load, monotony, and strain and dose-response relationships with maximal aerobic speed, maximal oxygen uptake, and isokinetic strength in professional soccer players. *PLoS One*. 2019; 14(12):e0225522. https://doi.org/10.1371/journal.pone.0225522.
2. Li C, Wang JCK, Pyun DY. Talent development environmental factors in sport: a review and taxonomic classification. *Quest*. 2014;66(4):433–447. https://doi.org/10.1080/00336297.2014.944715.
3. Kim DS, Wheeler MT, Ashley EA. The genetics of human performance. *Nat Rev Genet*. 2022;23(1):40–54. https://doi.org/10.1038/s41576-021-00400-5.
4. Frontera WR, Ochala J. Skeletal muscle: a brief review of structure and function. *Calcif Tissue Int*. 2015;96(3):183–195. https://doi.org/10.1007/s00223-014-9915-y.
5. Stanelle ST, Crouse SF, Heimdal TR, Riechman SE, Remy AL, Lambert BS. Predicting muscular strength using demographics, skeletal dimensions, and body composition measures. *Sports Med Health Sci*. 2021;3(1):34–39. https://doi.org/10.1016/j.smhs.2021.02.001.
6. Suchomel TJ, Nimphius S, Stone MH. The importance of muscular strength in athletic performance. *Sports Med*. 2016;46(10):1419–1449. https://doi.org/10.1007/s40279-016-0486-0.
7. Suchomel TJ, Nimphius S, Bellon CR, Stone MH. The importance of muscular strength: training considerations. *Sports Med*. 2018;48(4):765–785. https://doi.org/10.1007/s40279-018-0862-z.
8. Vandewoude MF, Alish CJ, Sauer AC, Hegazi RA. Malnutrition-sarcopenia syndrome: is this the future of nutrition screening and assessment for older adults? *J Aging Res*. 2012;2012:651570. https://doi.org/10.1155/2012/651570.
9. Braddom RL, ed. *Physical Medicine and Rehabilitation*. fourth ed. Philadelphia: PA: Elsevier; 2011. https://bit.ly/3yiz3Sw. Accessed June 26, 2024.
10. Leite MM, de Sousa Neto IV, Dutra MT, et al. Predictive models of muscle strength in older people with type 2 diabetes mellitus. *Clin Interv Aging*. 2023;18:1535–1546. https://doi.org/10.2147/CIA.S414620.
11. Ahsan M, Ahmed MD, Azeem K. Role of predictive modeling and personalized modeling in the enhancement of athletic performance. *Saudi J Sports Med*. 2023; 23(1):7–9. https://doi.org/10.4103/sjsm.sjsm_7_23.

12. Neder JA, Nery LE, Shinzato GT, Andrade MS, Peres C, Silva AC. Reference values for concentric knee isokinetic strength and power in nonathletic men and women from 20 to 80 years old. *J Orthop Sports Phys Ther*. 1999;29(2):116–126. https://doi.org/10.2519/jospt.1999.29.2.116.
13. Harbo T, Brincks J, Andersen H. Maximal isokinetic and isometric muscle strength of major muscle groups related to age, body mass, height, and sex in 178 healthy subjects. *Eur J Appl Physiol*. 2012;112(1):267–275. https://doi.org/10.1007/s00421-011-1975-3.
14. Hammami R, Chaouachi A, Makhlouf I, Granacher U, Behm DG. Associations between balance and muscle strength, power performance in male youth athletes of different maturity status. *Pediatr Exerc Sci*. 2016;28(4):521–534. https://doi.org/10.1123/pes.2015-0231.
15. Silva AM, Shen W, Heo M, et al. Ethnicity-related skeletal muscle differences across the lifespan. *Am J Hum Biol*. 2010;22(1):76–82. https://doi.org/10.1002/ajhb.20956.
16. Handelsman DJ. Sex differences in athletic performance emerge coinciding with the onset of male puberty. *Clin Endocrinol*. 2017;87(1):68–72. https://doi.org/10.1111/cen.13350.
17. Stark T, Walker B, Phillips JK, Fejer R, Beck R. Hand-held dynamometry correlation with the gold standard isokinetic dynamometry: a systematic review. *Pharm Manag PM R*. 2011;3(5):472–479. https://doi.org/10.1016/j.pmrj.2010.10.025.
18. Lockie RG, Ruvalcaba TR, Stierli M, Dulla JM, Dawes JJ, Orr RM. Waist circumference and waist-to-hip ratio in law enforcement agency recruits: relationship to performance in physical fitness tests. *J Strength Condit Res*. 2020;34(6):1666–1675. https://doi.org/10.1519/JSC.0000000000002825.
19. Lukaski H, Raymond-Pope CJ. New frontiers of body composition in sport. *Int J Sports Med*. 2021;42(7):588–601. https://doi.org/10.1055/a-1373-5881.
20. Toth AJ, Ramsbottom N, Constantin C, Milliet A, Campbell MJ. The effect of expertise, training and neurostimulation on sensory-motor skill in esports. *Comput Hum Behav*. 2021;121:106782. https://doi.org/10.1016/j.chb.2021.106782.
21. McKinney J, Velghe J, Fee J, Isserow S, Drezner JA. Defining athletes and exercisers. *Am J Cardiol*. 2019;123(3):532–535. https://doi.org/10.1016/j.amjcard.2018.11.001.
22. Park J. Using physical activity levels to estimate energy requirements of female athletes. *J Exerc Nutrition Biochem*. 2019;23(4):1–5. https://doi.org/10.20463/jenb.2019.0024.
23. Kavouras SA, Maraki MI, Kollia M, Gioxari A, Jansen LT, Sidossis LS. Development, reliability and validity of a physical activity questionnaire for estimating energy expenditure in Greek adults. *Sci Sports*. 2016;31(3):e47–e53. https://doi.org/10.1016/j.scispo.2016.01.007.
24. Magkos F, Manios Y, Babaroutsi E, Sidossis LS. Development and validation of a food frequency questionnaire for assessing dietary calcium intake in the general population. *Osteoporosis Int*. 2006;17(2):304–312. https://doi.org/10.1007/s00198-004-1679-1.
25. Ministry of Health and Welfare. Dietary guidelines for adults in Greece. *Arch Hellenic Med*. 1999;16:516–524. https://tinyurl.com/3e97m3ke. Accessed September 29, 2023.
26. Rupasinghe W, Wickramaratne MN. A comprehensive review on dietary assessment methods in epidemiological studies. *Publ Health Nutr*. 2020;3(1):204–211. https://bit.ly/3LONXTn. Accessed July 29, 2024.
27. Biodex Medical Systems Inc. *Biodex System 3 PRO. Shirley, NY: Biodex Medical Systems*. Inc.; 2015. Published online https://bit.ly/4bXG09i. Accessed February 10, 2023.
28. Virgile A, Bishop C. A narrative review of limb dominance: task specificity and the importance of fitness testing. *J Strength Condit Res*. 2021;35(3):846–858. https://doi.org/10.1519/JSC.0000000000003851.
29. van Melick N, Meddeler BM, Hoogeboom TJ, Nijhuis-van der Sanden MWG, van Cingel REH. How to determine leg dominance: the agreement between self-reported and observed performance in healthy adults. *PLoS One*. 2017;12(12):e0189876. https://doi.org/10.1371/journal.pone.0189876.
30. Schindler IFSR, Pontes SS, Bertoni MBM, et al. A systematic review of isokinetic muscle strength in a healthy population with special reference to age and gender. *Sport Health*. 2023;15(3):328–332. https://doi.org/10.1177/19417381221146258.
31. Maffiuletti NA, Bizzini M, Desbrosses K, Babault N, Munzinger U. Reliability of knee extension and flexion measurements using the con-trex isokinetic dynamometer. *Clin Physiol Funct Imag*. 2007;27(6):346–353. https://doi.org/10.1111/j.1475-097X.2007.00758.x.
32. Isohelix. Buccal-prep Plus DNA isolation kit. *Harrietsham, Kent: Isohelix*; 2023. Published online https://isohelix.com/products/bpp/. Accessed June 20, 2024.
33. ThermoFisher Scientific. iPrep pure link gDNA blood kit. Waltham, MA: ThermoFisher scientific. Published online https://bit.ly/4bXFEiY; 2024. Accessed June 20, 2024.
34. Illumina. Infinium global screening array-24 kit. Published online https://bit.ly/3A20lwU; 2024. Accessed June 20, 2024.
35. ThermoFisher Scientific. Axiom precision medicine diversity array Plus kit, 96-format. Published online https://bit.ly/3Yi4oPK; 2024. Accessed June 20, 2024.
36. Illumina. Infinium CoreExome-24 v1.4 BeadChip. Published online https://bit.ly/3WqhB6j; 2024. Accessed June 20, 2024.
37. Knechtle B, Knechtle P, Schulze I, Kohler G. Upper arm circumference is associated with race performance in ultra-endurance runners. *Br J Sports Med*. 2008;42(4):295–299. https://doi.org/10.1136/bjsm.2007.038570.
38. Maillard F, Pereira B, Boisseau N. Effect of high-intensity interval training on total, abdominal and visceral Fat Mass: a Meta-Analysis. *Sports Med*. 2018;48(2):269–288. https://doi.org/10.1007/s40279-017-0807-y.
39. Harrell Jr F. Hmisc: harrell miscellaneous. Published online https://bit.ly/3WmCZJJ; 2023. Accessed June 20, 2024.
40. R Core Team. *A Language and Environment for Statistical Computing*. Vienna, Austria: R Foundation for Statistical Computing; 2021. Published online https://bit.ly/47hJEtY. Accessed September 8, 2024.
41. Wright K. Plot a correlogram. Published online https://bit.ly/4bXho0k; 2021. Accessed June 20, 2024.
42. Ashtary-Larky D, Nazary Vanani A, Hosseini SA, Rafie R, Abbasnezhad A, Alipour M. Relationship between the body fat percentage and anthropometric measurements in athletes compared with non-athletes. *Zahedan J Res in Med Sci*. 2018;20(2):e10422. https://doi.org/10.5812/zjrms.10422.
43. Hetherington-Rauth M, Baptista F, Sardinha LB. BIA-assessed cellular hydration and muscle performance in youth, adults, and older adults. *Clin Nutr*. 2020;39(8):2624–2630. https://doi.org/10.1016/j.clnu.2019.11.040.
44. Li K, Hewson DJ, Duchêne J, Hogrel JY. Predicting maximal grip strength using hand circumference. *Man Ther*. 2010;15(6):579–585. https://doi.org/10.1016/j.math.2010.06.010.
45. Millot F, Guilhot J, Baruchel A, et al. Growth deceleration in children treated with imatinib for chronic myeloid leukaemia. *Eur J Cancer*. 2014;50(18):3206–3211. https://doi.org/10.1016/j.ejca.2014.10.007.
46. Danneskiold-Samsøe B, Bartels EM, Bülow PM, et al. Isokinetic and isometric muscle strength in a healthy population with special reference to age and gender. *Acta Physiol*. 2009;673:1–68. https://doi.org/10.1111/j.1748-1716.2009.02022.x, 197Suppl.
47. Beunen G, Thomis M. Muscular strength development in children and adolescents. *Pediatr Exerc Sci*. 2000;12(2):174–197. https://doi.org/10.1123/pes.12.2.174.
48. Faulkner JA, Larkin LM, Claflin DR, Brooks SV. Age-related changes in the structure and function of skeletal muscles. *Clin Exp Pharmacol Physiol*. 2007;34(11):1091–1096. https://doi.org/10.1111/j.1440-1681.2007.04752.x.
49. Biltz NK, Collins KH, Shen KC, Schwartz K, Harris CA, Meyer GA. Infiltration of intramuscular adipose tissue impairs skeletal muscle contraction. *J Physiol*. 2020;598(13):2669–2683. https://doi.org/10.1113/JP279595.
50. Hu K, Deya Edelen E, Zhuo W, et al. Understanding the consequences of fatty bone and fatty muscle: how the osteosarcopenic adiposity phenotype uncovers the deterioration of body composition. *Metabolites*. 2023;13(10):1056. https://doi.org/10.3390/metabo13101056.
51. Casanova N, Willig R, Soares D, et al. Relationship between anthropometric attributes and physical fitness levels in young male Portuguese futsal players. *Open Sports Sci J*. 2024;17(1):e1875399X290477. https://doi.org/10.2174/011875399X290477240329065522.
52. Popadic Gacesa J, Barak O, Jakovljevic DK. Body mass index and body fat content in elite athletes. *Exerc Qual Life*. 2011;3(2):43–48. https://doi.org/10.31382/EQOL201102065P.
53. Cole TJ, Lobstein T. Extended international (IOTF) body mass index cut-offs for thinness, overweight and obesity. *Pediatr Obes*. 2012;7(4):284–294. https://doi.org/10.1111/j.2047-6310.2012.00064.x.
54. Okada T, Huxel KC, Nesser TW. Relationship between core stability, functional movement, and performance. *J Strength Condit Res*. 2011;25(1):252–261. https://doi.org/10.1519/JSC.0b013e3181b22b3e.
55. Liu Y, Zhang F, Gan L, et al. Associations between waist circumference and executive function among Chinese Tibetan adolescents living at high altitude. *Front Nutr*. 2023;10:996785. https://doi.org/10.3389/fnut.2023.996785.
56. Castillo C, Carnicero JA, de la Torre MÁ, et al. Nonlinear relationship between waist to hip ratio, weight and strength in elders: is gender the key? *Biogerontology*. 2015;16(5):685–692. https://doi.org/10.1007/s10522-015-9582-z.
57. Mauvais-Jarvis F, ed. *Sex and Gender Factors Affecting Metabolic Homeostasis, Diabetes and Obesity*. first ed. Cham, Switzerland: Springer; 2018. http://www.springer.com/series/5584. Accessed September 20, 2023.
58. Janicijevic D, Knezevic OM, Garcia-Ramos A, Cvetic D, Mirkov DM. Isokinetic testing: sensitivity of the force-velocity relationship assessed through the two-point method to discriminate between muscle groups and participants' physical activity levels. *Int J Environ Res Publ Health*. 2020;17(22):8570. https://doi.org/10.3390/ijerph17228570.
59. Senefeld JW, Hunter SK. Hormonal basis of biological sex differences in human athletic performance. *Endocrinology*. 2024;165(5):bqae036. https://doi.org/10.1210/endocr/bqae036.
60. Sandbakk Ø, Solli GS, Holmberg HC. Sex differences in world-record performance: the influence of sport discipline and competition duration. *Int J Sports Physiol Perform*. 2018;13(1):2–8. https://doi.org/10.1123/ijspp.2017-0196.
61. Tiller NB, Elliott-Sale KJ, Knechtle B, Wilson PB, Roberts JD, Millet GY. Do sex differences in physiology confer a female advantage in ultra-endurance sport? *Sports Med*. 2021;51(5):895–915. https://doi.org/10.1007/s40279-020-01417-2.
62. Azam M, Ali A, Akbar S, Bashir M, Chung HC. Gender differences while performing an everyday perceptual-motor task. *Humanities Soc Sci Rev*. 2021;9(3):1504–1513. https://doi.org/10.18510/hssr.2021.93151.
63. Navarro M, van der Kamp J, Schor P, Savelsbergh GJP. Implicit learning increases shot accuracy of football players when making strategic decisions during penalty kicking. *Hum Mov Sci*. 2018;61:72–80. https://doi.org/10.1016/j.humov.2018.07.004.
64. Lulic-Kuryllo T, Inglis JG. Sex differences in motor unit behavior: a review. *J Electromyogr Kinesiol*. 2022;66:102689. https://doi.org/10.1016/j.jelekin.2022.102689.
65. Helsen WF, Starkes JL. A multidimensional approach to skilled perception and performance in sport. *Appl Cognit Psychol*. 1999;13(1):1–27. https://doi.org/10.1002/(SICI)1099-0720(199902)13:1<1::AID-ACP540>3.0.CO;2-T.
66. Dorø E, Martin R, Ratel S, Duchø P, Bedu M, Van Praagh E. Gender differences in peak muscle performance during growth. *Int J Sports Med*. 2005;26(4):274–280. https://doi.org/10.1055/s-2004-821001'Published.

67. Toskić L, Dopsaj M, Toskić D, Marković M. Isokinetic muscle power of the knee extensor and flexor muscles among differently trained people in relation to gender. *Hum Mov*. 2020;21(3):81–89. https://doi.org/10.5114/hm.2020.91349.
68. Handelsman DJ, Hirschberg AL, Bermon S. Circulating testosterone as the hormonal basis of sex differences in athletic performance. *Endocr Rev*. 2018;39(5):803–829. https://doi.org/10.1210/er.2018-00020.
69. Grund A, Krause H, Kraus M, Siewers M, Rieckert H, Müller MJ. Association between different attributes of physical activity and fat mass in untrained, endurance- and resistance-trained men. *Eur J Appl Physiol*. 2001;84(4):310–320. https://doi.org/10.1007/s004210000369.
70. Zech A, Hollander K, Junge A, et al. Sex differences in injury rates in team-sport athletes: a systematic review and meta-regression analysis. *J Sport Health Sci*. 2022;11(1):104–114. https://doi.org/10.1016/j.jshs.2021.04.003.
71. Hill AV, Sec RS. The heat of shortening and the dynamic constants of muscle. *Proc R Soc Lond B Biol Sci*. 1938;126(843):136–195. https://doi.org/10.1098/rspb.1938.0050.
72. Drouin JM, Valovich-mcLeod TC, Shultz SJ, Gansneder BM, Perrin DH. Reliability and validity of the Biodex system 3 pro isokinetic dynamometer velocity, torque and position measurements. *Eur J Appl Physiol*. 2004;91(1):22–29. https://doi.org/10.1007/s00421-003-0933-0.
73. Gomes M, Santos P, Correia P, Pezarat-Correia P, Mendonca GV. Sex differences in muscle fatigue following isokinetic muscle contractions. *Sci Rep*. 2021;11(1):8141. https://doi.org/10.1038/s41598-021-87443-0.
74. Hunter SK, Angadi S, Bhargava A, et al. The biological basis of sex differences in athletic performance: consensus statement for the American College of Sports Medicine. *Med Sci Sports Exerc*. 2023;55(12):2328–2360. https://doi.org/10.1249/MSS.0000000000003300.
75. Falk B, Brunton L, Dotan R, et al. Muscle strength and contractile kinetics of isometric elbow flexion in girls and women. *Pediatr Exerc Sci*. 2009;21(3):354–364. https://doi.org/10.1123/pes.21.3.354.